

LECTURE 14

QUICKSORT

MCS 275 Spring 2023

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LECTURE 14: QUICKSORT

Reminders and announcements:

- Project 2 due 6pm Fri 24 Feb.
- Project 2 autograder opens by Mon 20 Feb.
 - Having at least partial work ready to submit at that time is a good goal.

TRANSFORMATION VS MUTATION

Last time we wrote a mergesort function that acts as a transformation: A list is given as input, a new sorted list is returned.

Another approach we could consider is sorting as a mutation: A list is provided, the function reorders its items and returns nothing.

IN PLACE

A sorting transformation always uses an amount of extra memory proportional to the size of the list. (It needs a second list to store the output.)

A sort that operates as a mutation has the possibility of using only a fixed amount of memory to do its work.

Doing so is called an **in place** sorting method.

QUICKSORT

A recursive in place sorting method that, like mergesort, is reasonably efficient and widely used.

PARTITION

Let's first study something weaker than sorting.

Given a list L , let p be the last element of L .

We want to rearrange L so that it looks like:

$$[\text{items} < p, \mathbf{p}, \text{items} \geq p]$$

We say L has been **partitioned** at p , and we call p the **pivot**.

PARTITION ALGORITHM IDEA

Scan through the list, moving things smaller than the pivot to the beginning.

PARTITION ALGORITHM VISUALIZATION

76235814

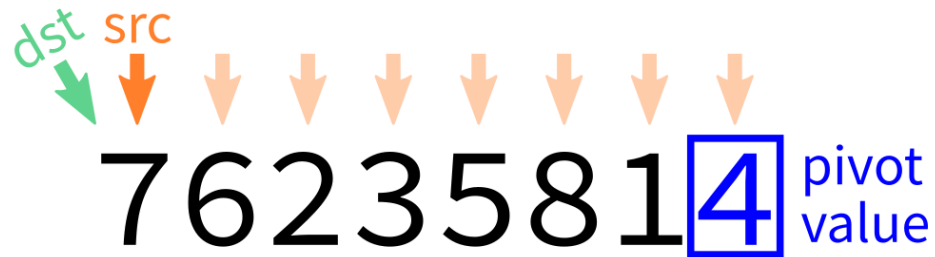
PARTITION ALGORITHM VISUALIZATION

76235814 pivot
value

PARTITION ALGORITHM VISUALIZATION

dst src
76235814 pivot
value

PARTITION ALGORITHM VISUALIZATION



PARTITION ALGORITHM VISUALIZATION

dst src
7 6 2 3 5 8 1 4 pivot
value

PARTITION ALGORITHM VISUALIZATION

dst src
7 6 2 3 5 8 1 4 pivot value

$L[\text{src}] \geq \text{pivot}$: do nothing

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
7 6 2 3 5 8 1 **4** pivot
value

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
7 6 2 3 5 8 1 4 pivot
value

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
7 6 2 3 5 8 1 4 pivot
value

$L[\text{src}] \geq \text{pivot}$: do nothing

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
7 6 2 3 5 8 1 **4** pivot
value

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
7 6 2 3 5 8 1 **4** pivot
 value

PARTITION ALGORITHM VISUALIZATION

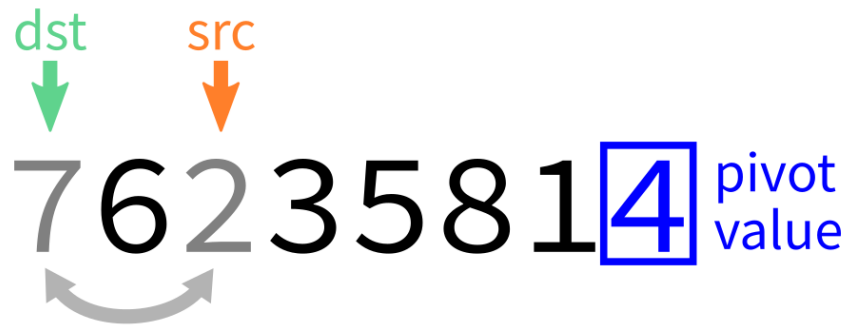
dst src
↓ ↓
7 6 2 3 5 8 1 **4** pivot
 value

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
7 6 2 3 5 8 1 4 pivot
value

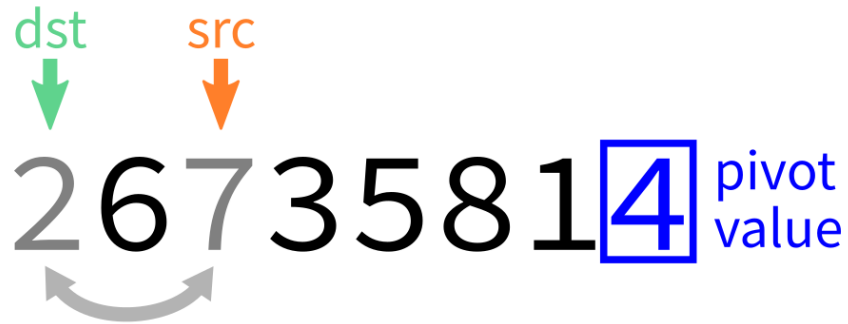
$L[\text{src}] < \text{pivot}$: **swap** $L[\text{src}], L[\text{dst}]$

PARTITION ALGORITHM VISUALIZATION



$L[\text{src}] < \text{pivot}$: **swap** $L[\text{src}], L[\text{dst}]$

PARTITION ALGORITHM VISUALIZATION



$L[src] < \text{pivot}$: **swap** $L[src], L[dst]$

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
2 6 7 3 5 8 1 **4** pivot
 value

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
2 6 7 3 5 8 1 **4** pivot
value

PARTITION ALGORITHM VISUALIZATION

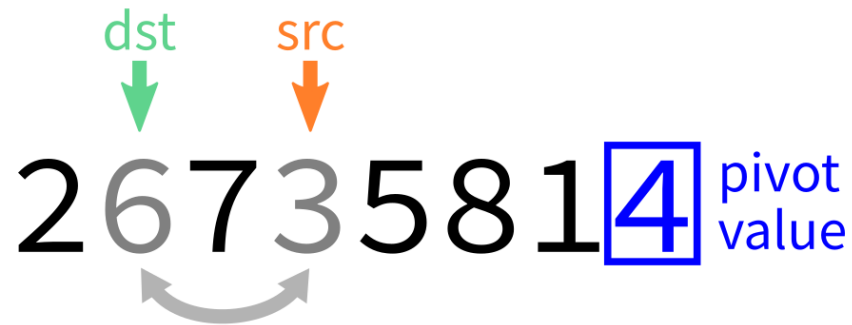
dst src
↓ ↓
2 6 7 3 5 8 1 **4** pivot
 value

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
2 6 7 3 5 8 1 4 pivot
value

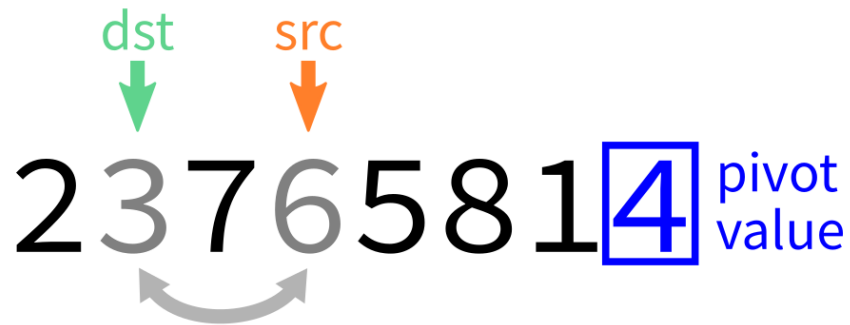
$L[src] < \text{pivot}$: **swap** $L[src], L[dst]$

PARTITION ALGORITHM VISUALIZATION



$L[\text{src}] < \text{pivot}$: **swap** $L[\text{src}], L[\text{dst}]$

PARTITION ALGORITHM VISUALIZATION



$L[src] < \text{pivot}$: **swap** $L[src], L[dst]$

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
2 3 7 6 5 8 1 **4** pivot
value

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
23765814 pivot
value

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
2 3 7 6 5 8 1 4 pivot
value

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
23765814 pivot
value

$L[src] \geq \text{pivot}$: do nothing

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
23765814 pivot
value

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
2376581 **4** pivot
 value

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
2 3 7 6 5 8 1 4 pivot
 value

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
23765814 pivot
 value

$L[\text{src}] \geq \text{pivot}$: do nothing

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
2376581 **4** pivot
 value

PARTITION ALGORITHM VISUALIZATION



PARTITION ALGORITHM VISUALIZATION

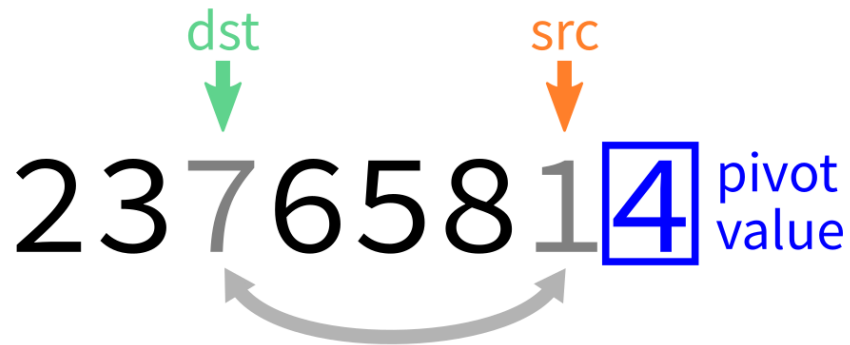
dst
↓
23765814 pivot
src
↓
value

PARTITION ALGORITHM VISUALIZATION

dst
↓
23765814 pivot
src
↓
value

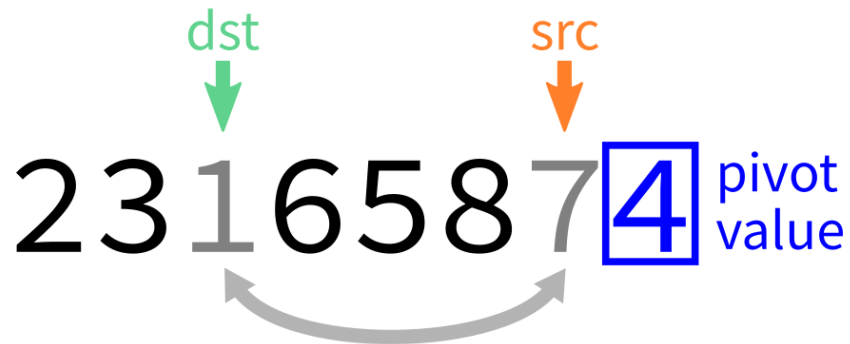
$L[src] < \text{pivot}$: **swap** $L[src], L[dst]$

PARTITION ALGORITHM VISUALIZATION



$L[src] < \text{pivot}$: **swap** $L[src], L[dst]$

PARTITION ALGORITHM VISUALIZATION



$L[src] < \text{pivot}$: **swap** $L[src], L[dst]$

PARTITION ALGORITHM VISUALIZATION

dst src
↓ ↓
2316587 **4** pivot
 value

PARTITION ALGORITHM VISUALIZATION

23165874 pivot value

The diagram illustrates the partitioning step of the quicksort algorithm. The array is [2, 3, 1, 6, 5, 8, 7, 4]. The pivot value is 4, which is highlighted with a blue box. A green arrow labeled 'dst' points to the element 6, and an orange arrow labeled 'src' points to the pivot value 4.

PARTITION ALGORITHM VISUALIZATION

23165874 pivot value

The diagram illustrates the partitioning step of the quicksort algorithm. The array is [2, 3, 1, 6, 5, 8, 7, 4]. The pivot value is 4, which is highlighted in a blue box. A green arrow labeled 'dst' points to the element 6, and an orange arrow labeled 'src' points to the pivot 4.

PARTITION ALGORITHM VISUALIZATION

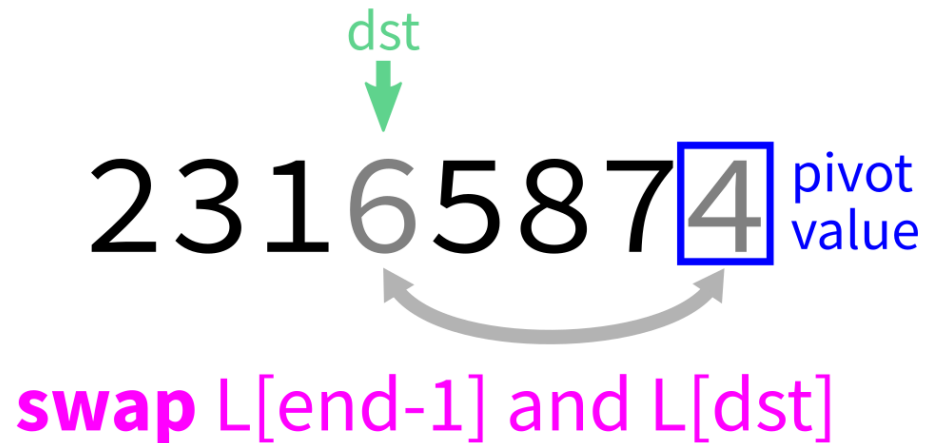
dst
↓
23165874 pivot
src value
↓

$L[src] \geq \text{pivot}$: do nothing

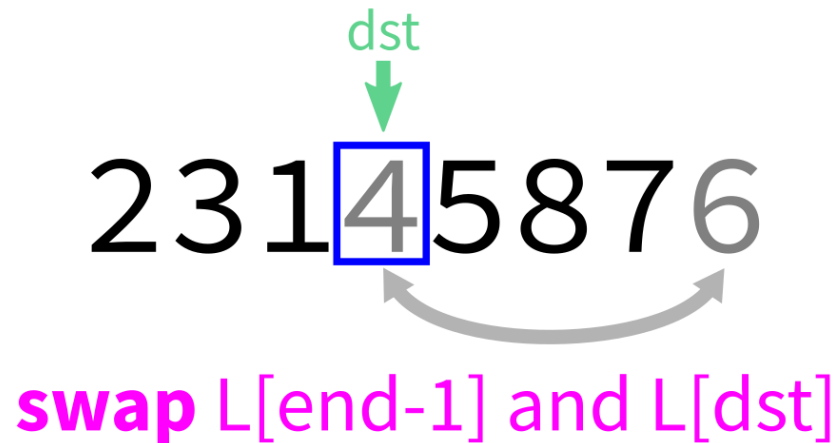
PARTITION ALGORITHM VISUALIZATION

dst
↓
23165874 pivot
value

PARTITION ALGORITHM VISUALIZATION



PARTITION ALGORITHM VISUALIZATION



PARTITION ALGORITHM VISUALIZATION

23145876

PARTITION ALGORITHM VISUALIZATION

23145876

PARTITION ALGORITHM VISUALIZATION

23145876

The image shows the array 23145876. The pivot element 4 is highlighted with a blue square. An orange bracket under the elements 2, 3, and 1 is labeled <4. A purple bracket under the elements 5, 8, 7, and 6 is labeled ≥4.

<4

≥4

AFTER PARTITION

The two chunks of the list on either side of the pivot may not be sorted.

But we could bring each of them closer to being sorted by partitioning them...

QUICKSORT SUMMARY

Starting with an unsorted list:

- If the list has 0 or 1 elements, return immediately.
- Otherwise, partition the list.
- Quicksort the part of the list before the pivot.
- Quicksort the part of the list after the pivot.

It's divide and conquer, but with no merge step. The hard work is instead in partitioning.

QUICKSORT VISUALIZATION

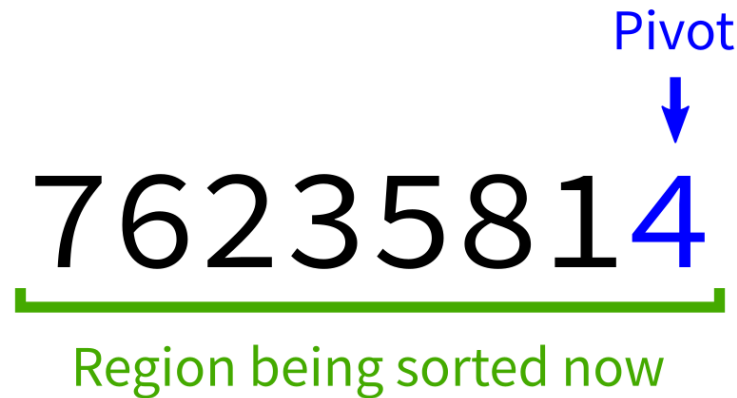
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QUICKSORT VISUALIZATION

76235814

Region being sorted now

QUICKSORT VISUALIZATION



QUICKSORT VISUALIZATION

Pivot

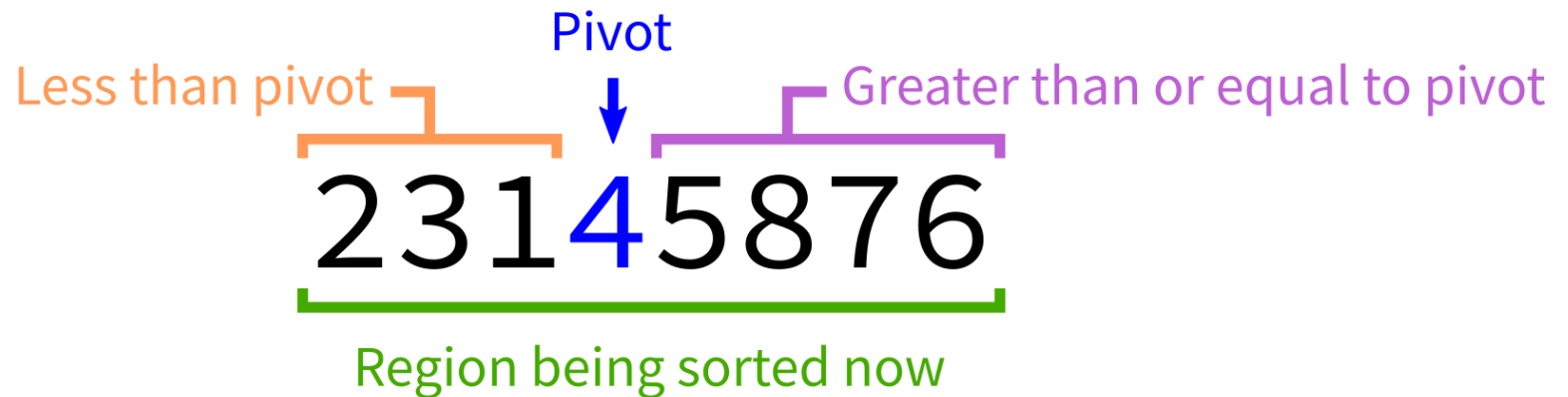


23145876



Region being sorted now

QUICKSORT VISUALIZATION



QUICKSORT VISUALIZATION

23145876

Region being sorted now

QUICKSORT VISUALIZATION

23145876



QUICKSORT VISUALIZATION

23145876

QUICKSORT VISUALIZATION

13245876



QUICKSORT VISUALIZATION

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QUICKSORT VISUALIZATION

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QUICKSORT VISUALIZATION

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QUICKSORT VISUALIZATION

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QUICKSORT VISUALIZATION

12345876



QUICKSORT VISUALIZATION

12345876

A horizontal green line is drawn underneath the number 5 in the sequence 12345876, indicating it as the pivot element in a Quicksort visualization.

QUICKSORT VISUALIZATION

12345876



QUICKSORT VISUALIZATION

12345678

QUICKSORT VISUALIZATION

12345678

A horizontal green line is drawn underneath the number 5 in the sequence 12345678, indicating it as the pivot element in a Quicksort visualization.

QUICKSORT VISUALIZATION

12345678



QUICKSORT VISUALIZATION

12345678



QUICKSORT VISUALIZATION

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QUICKSORT VISUALIZATION

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QUICKSORT VISUALIZATION

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QUICKSORT VISUALIZATION

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QUICKSORT VISUALIZATION

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QUICKSORT VISUALIZATION

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QUICKSORT VISUALIZATION

12345678

CODING TIME

Let's implement `quicksort` in Python.

Algorithm quicksort:

Input: list L and indices $start$ and end .

Goal: reorder elements of L so that $L[start : end]$ is sorted.

1. If $(end - start)$ is less than or equal to 1, return immediately.
2. Otherwise, call `partition(L)` to partition the list, letting m be the final location of the pivot.
3. Call `quicksort(L, start, m)` and `quicksort(L, m+1, end)` to sort the parts of the list on either side of the pivot.

Algorithm **partition**:

Input: list L and indices $start$ and end .

Goal: Take $L[end - 1]$ as a pivot, and reorder elements of L to partition $L[start : end]$ accordingly.

WHY DISCUSS ALGORITHMS?

Python lists have built-in `.sort()` method. Why talk about sorting?

1. Study cases of easy-to-explain problems solved in clever ways.
2. See patterns of thinking that work in other settings.

EVALUATING SORTS

Last time we discussed and implemented mergesort, developed by von Neumann (1945) and Goldstine (1947).

Today we discussed quicksort, first described by Hoare (1959) and the simpler partitioning scheme introduced by Lomuto.

But are these actually good ways to sort a list?

EFFICIENCY

Theorem: If you measure the time cost of mergesort in any of these terms

- Number of comparisons made
- Number of assignments (e.g. $L[i] = x$ counts as 1)
- Number of Python statements executed

then the cost to sort a list of length n is less than $Cn \log(n)$, for some constant C that only depends on which expense measure you chose.

ASYMPTOTICALLY OPTIMAL

$Cn \log(n)$ is pretty efficient for an operation that needs to look at all n elements. It's not linear in n , but it only grows a little faster than linear functions.

Furthermore, $Cn \log(n)$ is the best possible time for comparison sort of n elements (though different methods might have better C).

QUICKSORT

Is quicksort similarly efficient?

REFERENCES

- Recursion references from [Lecture 10](#).
- Sorting visualizations:
 - [2D visualization through color sorting](#) by Linus Lee
 - [Animated bar graph visualization of many sorting algorithms](#) by Alex Macy
 - Slanted line animated visualizations of [mergesort](#) and [quicksort](#) by Mike Bostock

REVISION HISTORY

- 2022-02-18 Last year's lecture on this topic finalized
- 2023-02-15 Updated for 2023

