

# COMP2521 24T1

## Sorting Algorithms (III)

### Divide-and-Conquer Sorting Algorithms

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merge sort  
quick sort

Merge Sort

Quick Sort

Comparison

Summary

divide-and-conquer algorithms  
**split** a problem into two or more subproblems,  
solve the subproblems **recursively**,  
and then **combine** the results.

**Merge Sort**

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Merging

Implementation

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# Merge Sort

## Merge Sort

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Invented by John von Neumann  
in 1945



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A divide-and-conquer sorting algorithm:

**split** the array into two roughly equal-sized parts

**recursively** sort each of the partitions

**merge** the two now-sorted partitions into a sorted array

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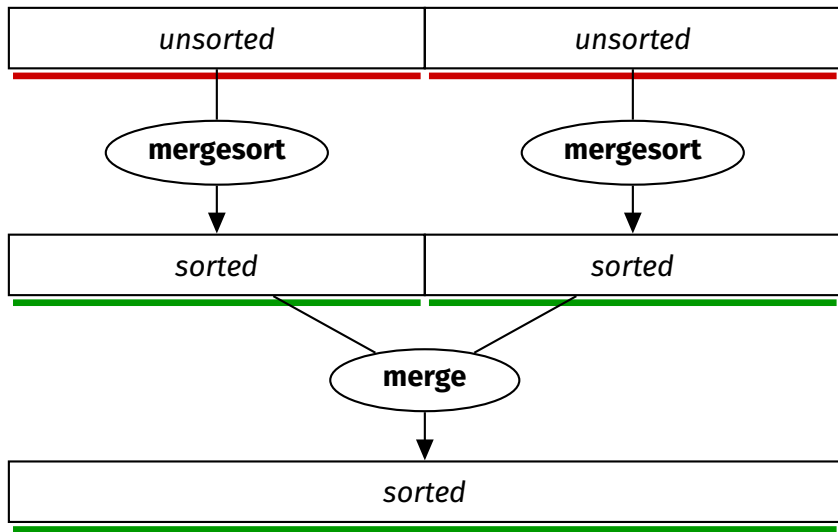
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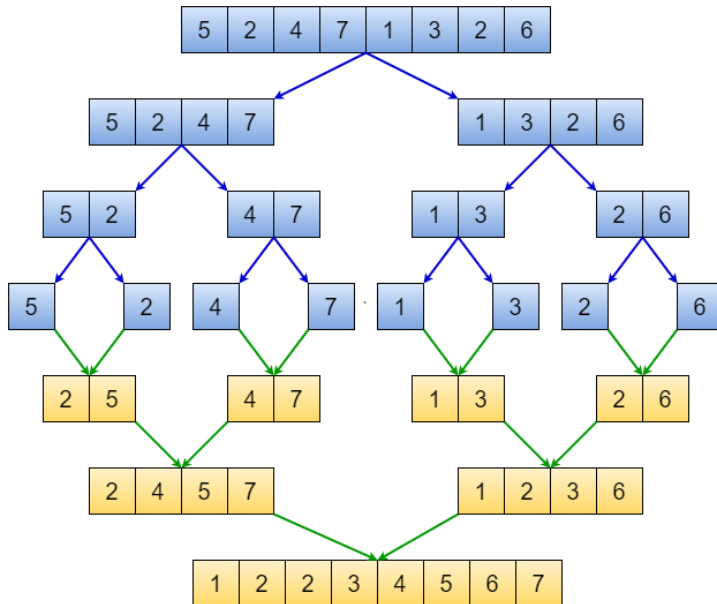
Merge Sort

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## How do we split the array?

- We don't physically split the array
- We simply calculate the midpoint of the array
  - $mid = (lo + hi) / 2$
- Then recursively sort each half by passing in appropriate indices
  - Sort between indices  $lo$  and  $mid$
  - Sort between indices  $mid + 1$  and  $hi$
- This means the time complexity of splitting the array is  $O(1)$



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## How do we merge two sorted subarrays?

- We merge the subarrays into a *temporary array*
- Keep track of the smallest element that has not been merged in each subarray
- Copy the smaller of the two elements into the temporary array
  - If the elements are equal, take from the left subarray
- Repeat until all elements have been merged
- Then copy from the temporary array back to the original array

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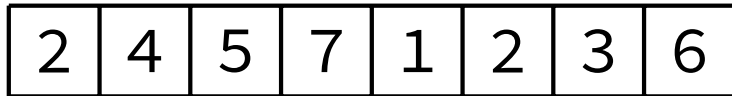
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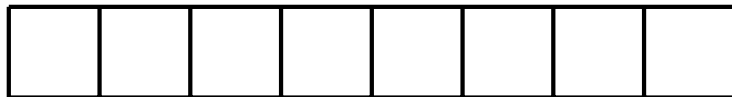
Sorting Lists

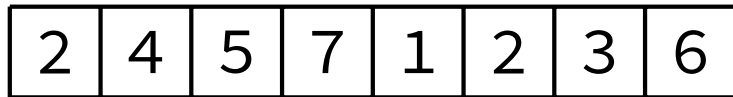
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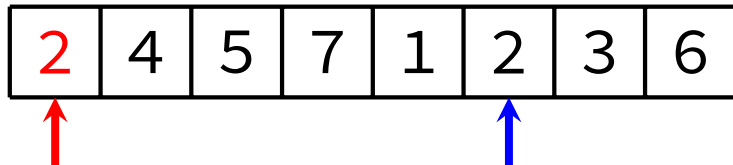
Summary



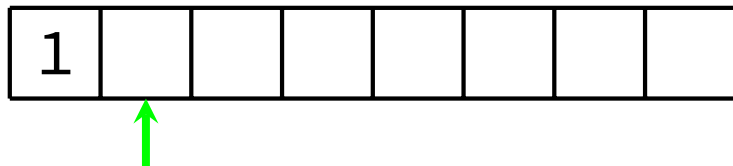


When items are equal, merge takes from the left subarray  
(this ensures stability)





When items are equal, merge takes from the left subarray  
(this ensures stability)



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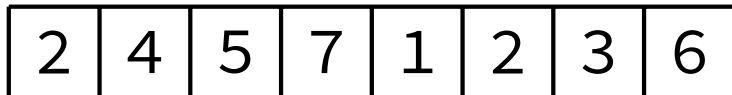
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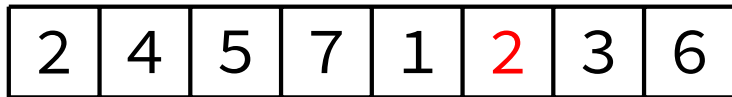
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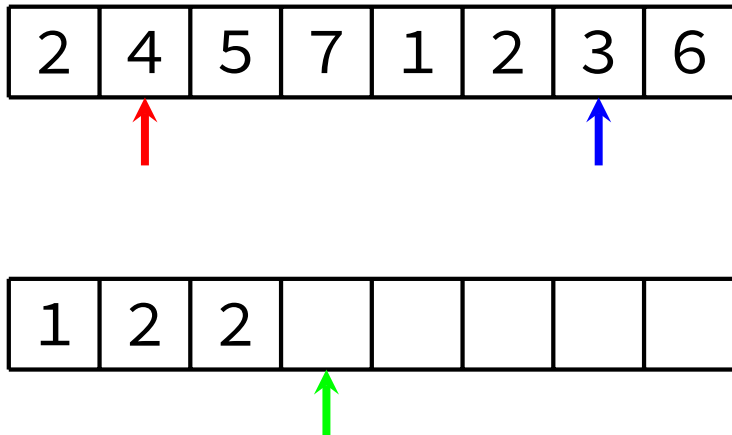
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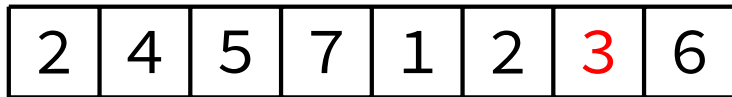
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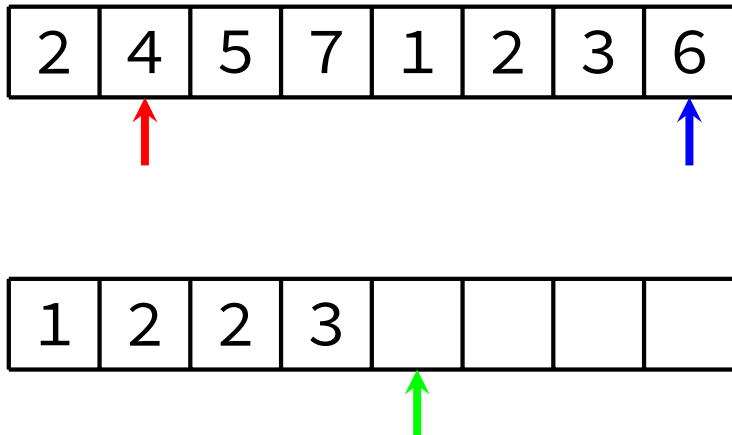
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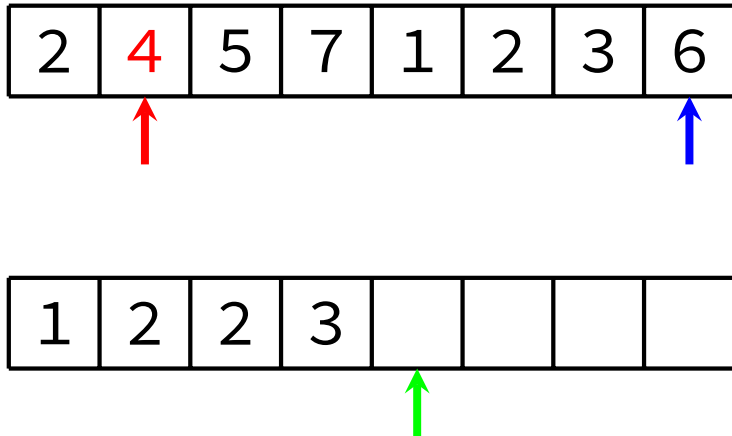
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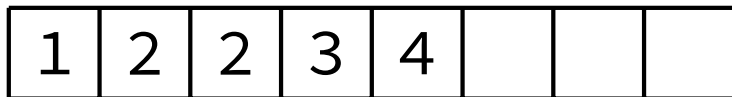
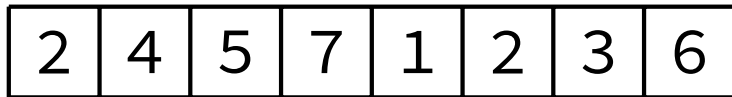
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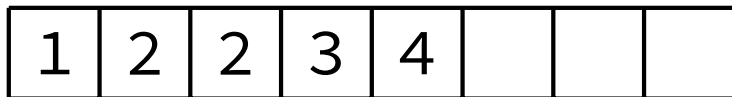
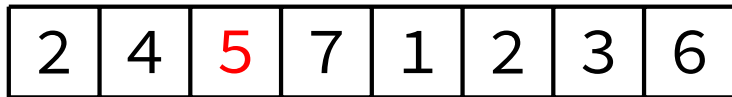
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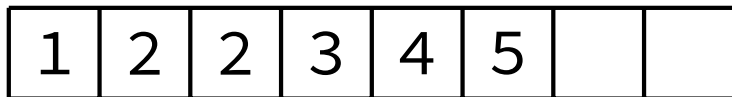
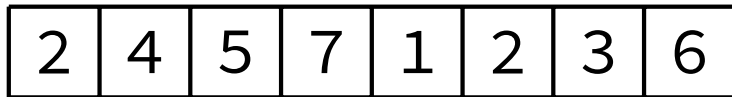
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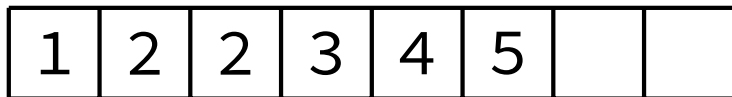
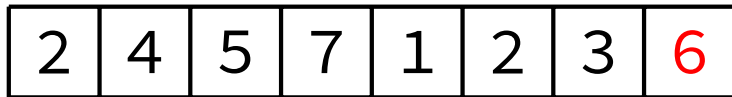
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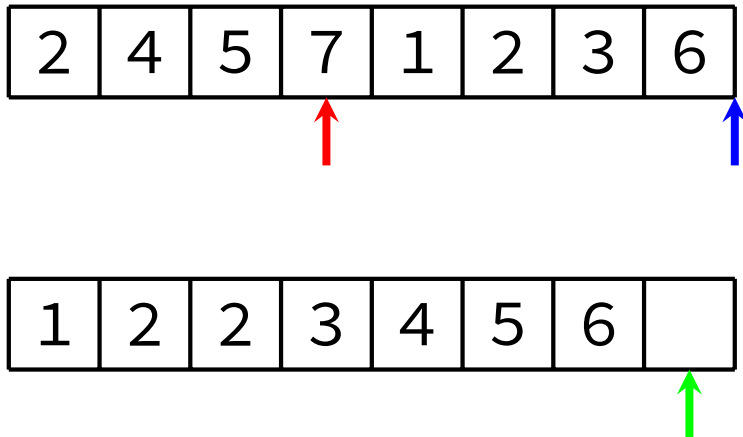
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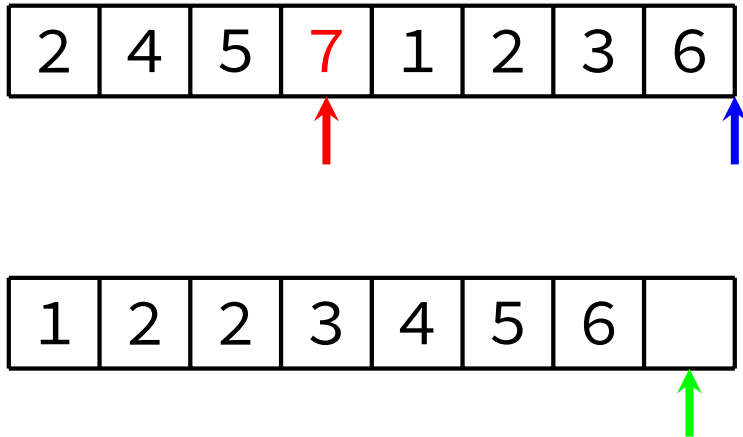
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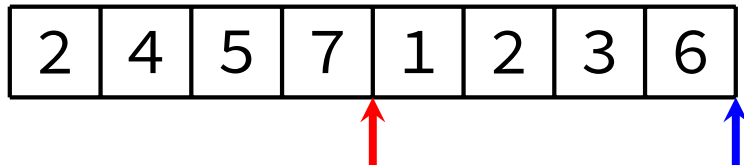
Sorting Lists

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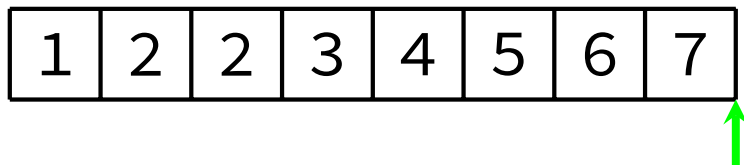
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Now copy back to original array



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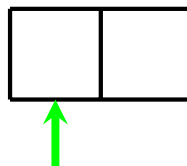
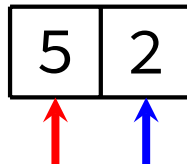
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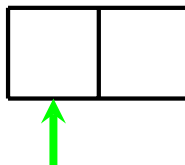
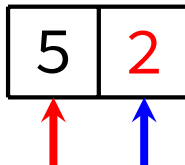
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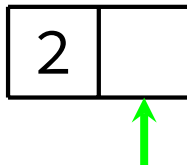
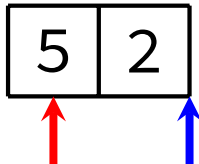
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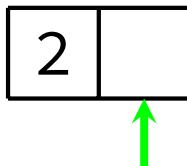
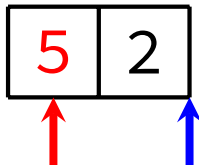
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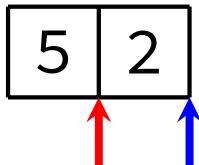
Sorting Lists

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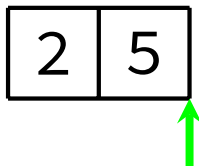
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Now copy back to original array



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- The time complexity of merging two sorted subarrays is  $O(n)$ , where  $n$  is the total number of elements in both subarrays
- Therefore:
  - Merging two subarrays of size 1 takes 2 “steps”
  - Merging two subarrays of size 2 takes 4 “steps”
  - Merging two subarrays of size 4 takes 8 “steps”
  - ...



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```
void mergeSort(Item items[], int lo, int hi) {  
    if (lo >= hi) return;  
    int mid = (lo + hi) / 2;  
    mergeSort(items, lo, mid);  
    mergeSort(items, mid + 1, hi);  
    merge(items, lo, mid, hi);  
}
```

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```
void merge(Item items[], int lo, int mid, int hi) {
    Item *tmp = malloc((hi - lo + 1) * sizeof(Item));
    int i = lo, j = mid + 1, k = 0;

    // Scan both segments, copying to `tmp'.
    while (i <= mid && j <= hi) {
        if (le(items[i], items[j])) {
            tmp[k++] = items[i++];
        } else {
            tmp[k++] = items[j++];
        }
    }

    // Copy items from unfinished segment.
    while (i <= mid) tmp[k++] = items[i++];
    while (j <= hi) tmp[k++] = items[j++];

    // Copy `tmp' back to main array.
    for (i = lo, k = 0; i <= hi; i++, k++) {
        items[i] = tmp[k];
    }

    free(tmp);
}
```

Merge Sort

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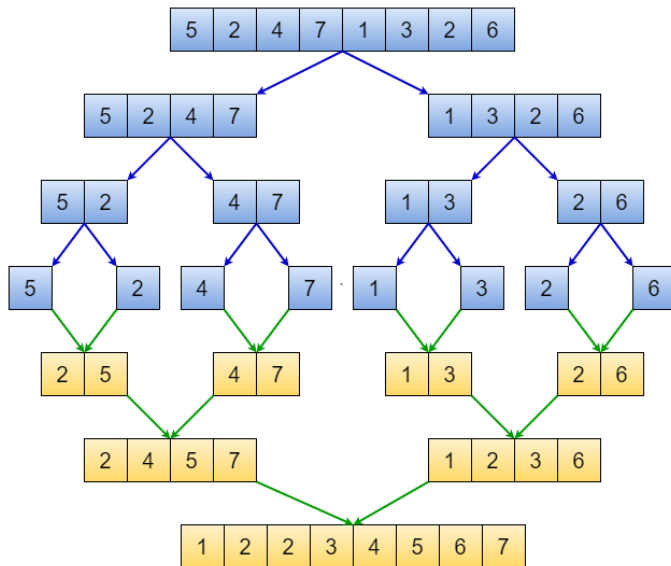
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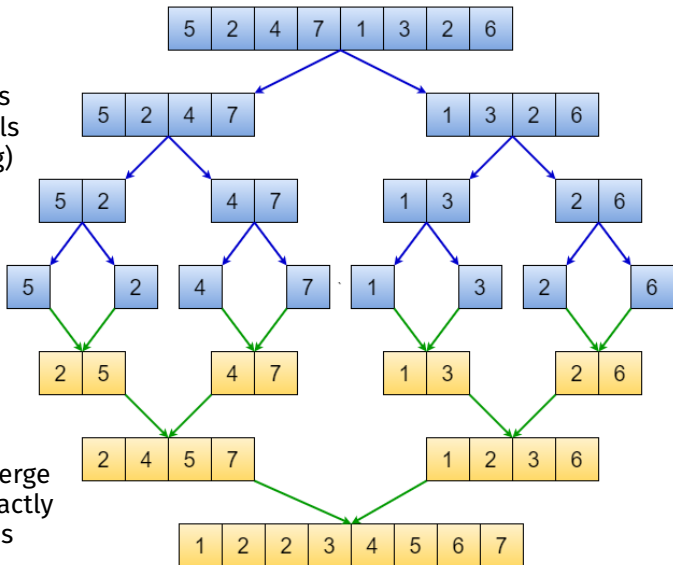
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Summary

**Split**  
 $n - 1$  splits  
( $\log_2 n$  levels  
of splitting)



$O(n)$

**Merge**  
We have to merge  
 $n$  numbers exactly  
 $\log_2 n$  times

$O(n \log n)$

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## Analysis:

- Merge sort splits the array into equal-sized partitions halving at each level  $\Rightarrow \log_2 n$  levels
- The same operations happen at every recursive level
- Each 'level' requires  $\leq n$  comparisons

## Therefore:

- The time complexity of merge sort is  $O(n \log n)$ 
  - Best-case, average-case, and worst-case time complexities are all the same

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**Note: Not required knowledge in COMP2521!**

Let  $T(n)$  be the time taken to sort  $n$  elements.

Splitting arrays into two halves takes constant time.

Merging two sorted arrays takes  $n$  steps.

So we have that:

$$T(n) = 2T(n/2) + n$$

Then the Master Theorem (see COMP3121) can be used to show that the time complexity is  $O(n \log n)$ .

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**Stable**

Due to taking from left subarray if items are equal during merge

**Non-adaptive**

$O(n \log n)$  best case, average case, worst case

**Not in-place**

Merge uses a temporary array of size up to  $n$

Note: Merge sort also uses  $O(\log n)$  stack space

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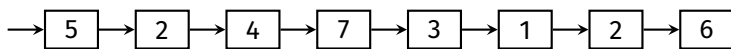
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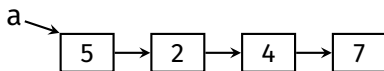
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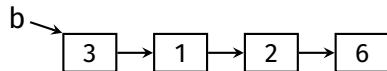
It is possible to apply merge sort on linked lists.



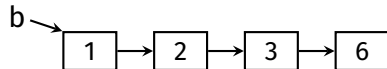
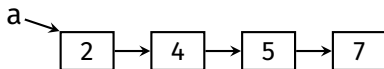
split



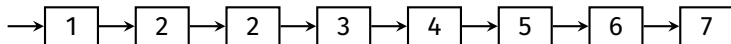
mergesort(a)



mergesort(b)



merge(a, b)





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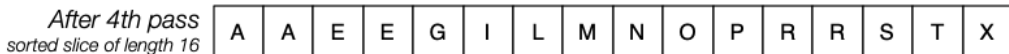
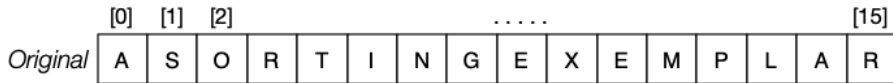
## Comparison

## Summary

An approach that works non-recursively!

- On each pass, our array contains sorted *runs* of length  $m$ .
- Initially,  $n$  sorted runs of length 1.
- The first pass merges adjacent elements into runs of length 2.
- The second pass merges adjacent elements into runs of length 4.
- Continue until we have a single sorted run of length  $n$ .

Can be used for *external* sorting;  
*e.g.*, sorting disk-file contents



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```
void mergeSortBottomUp(Item items[], int lo, int hi) {  
    for (int m = 1; m <= hi - lo; m *= 2) {  
        for (int i = lo; i <= hi - m; i += 2 * m) {  
            int end = min(i + 2 * m - 1, hi);  
            merge(items, i, i + m - 1, end);  
        }  
    }  
}
```

Merge Sort

**Quick Sort**

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Median-of-Three

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# Quick Sort

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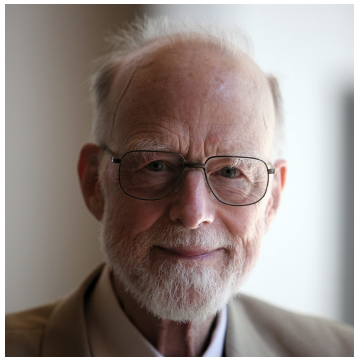
Improvements

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Invented by Tony Hoare  
in 1959



Merge Sort

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## Method:

- 1 Choose an item to be a pivot
- 2 Rearrange (partition) the array so that
  - All elements to the left of the pivot are less than (or equal to) the pivot
  - All elements to the right of the pivot are greater than (or equal to) the pivot
- 3 Recursively sort each of the partitions

## Merge Sort

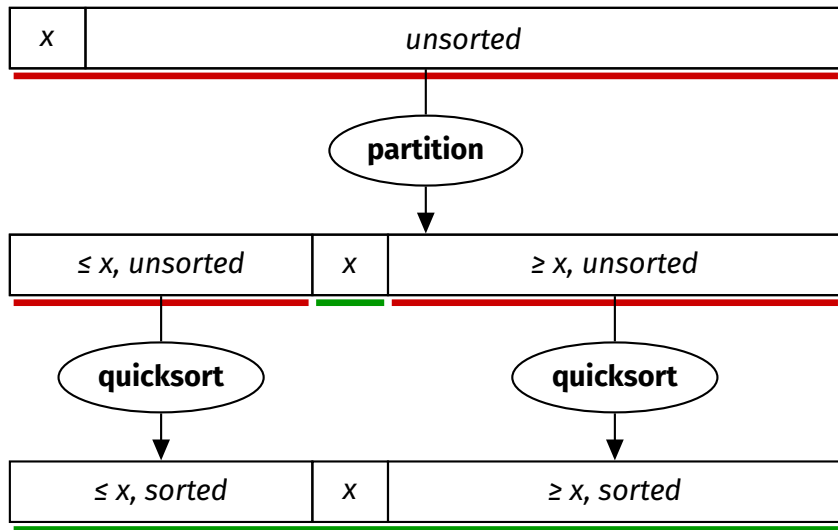
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Randomised

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## How to partition an array?

- Assume the pivot is stored at index  $l_0$
- Create index  $l$  to start of array ( $l_0 + 1$ )
- Create index  $r$  to end of array ( $hi$ )
- Until  $l$  and  $r$  meet:
  - Increment  $l$  until  $a[l]$  is greater than pivot
  - Decrement  $r$  until  $a[r]$  is less than pivot
  - Swap items at indices  $l$  and  $r$
- Swap the pivot with index  $l$  or  $l - 1$  (depending on the item at index  $l$ )



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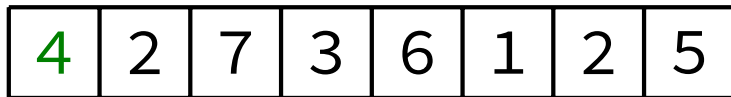
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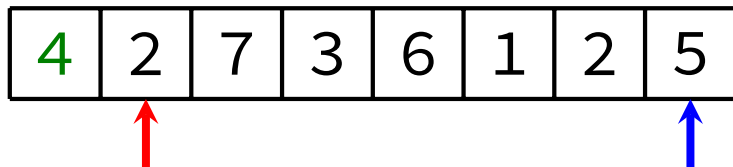
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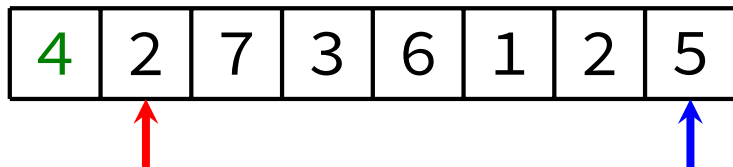
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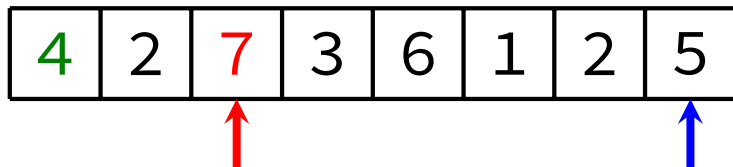
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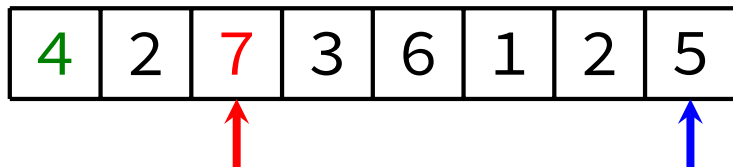
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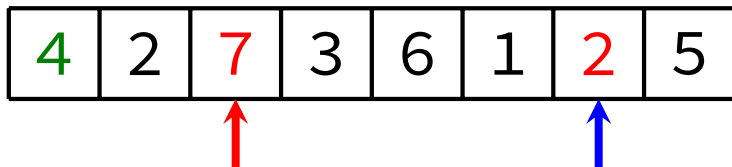
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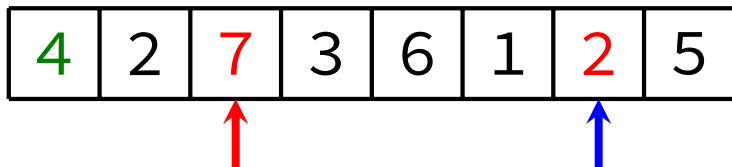
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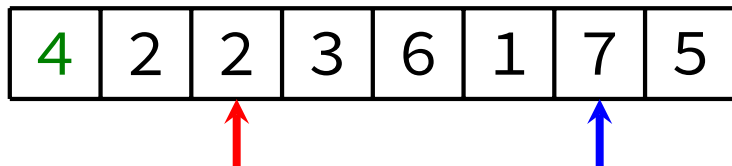
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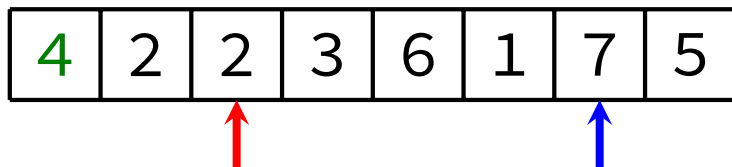
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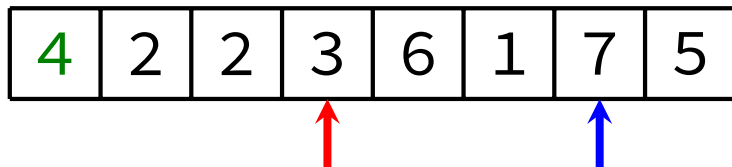
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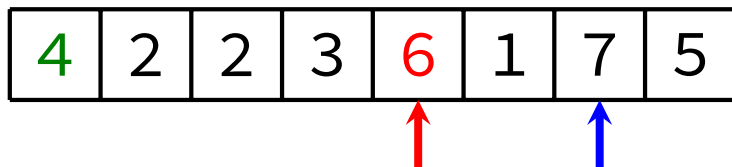
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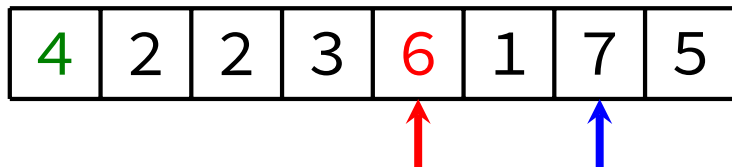
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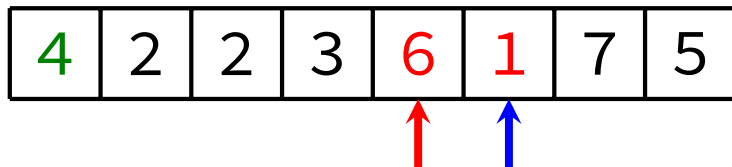
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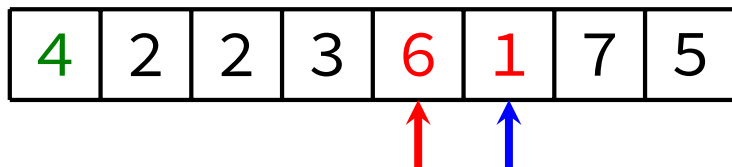
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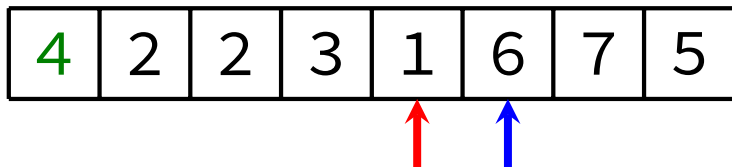
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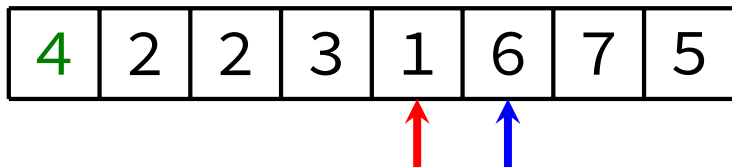
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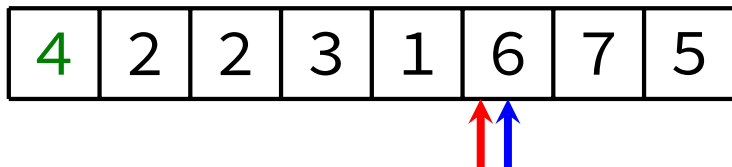
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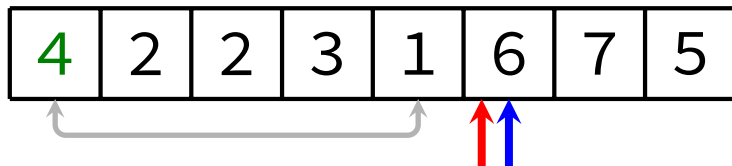
Improvements

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Swap the pivot into the middle (be careful!)



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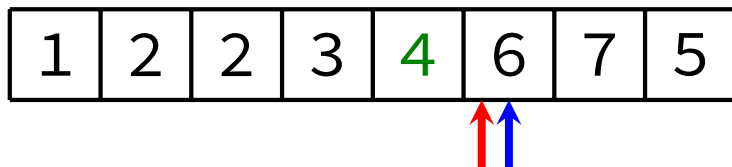
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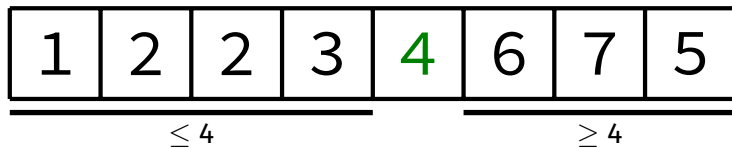
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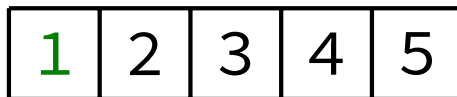
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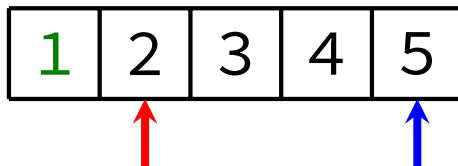
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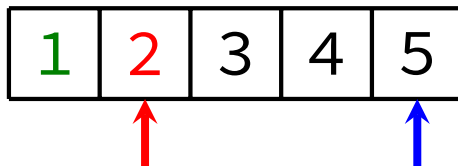
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Increment left index while element is  $\leq$  pivot



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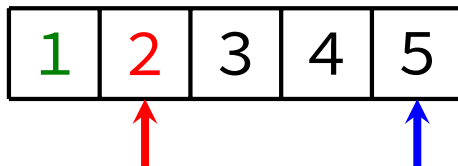
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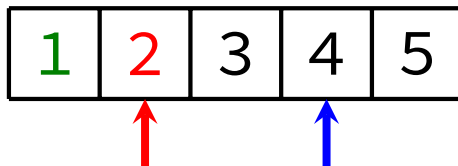
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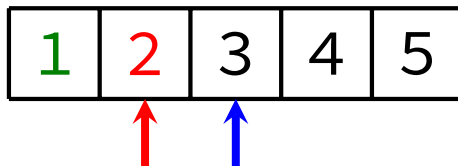
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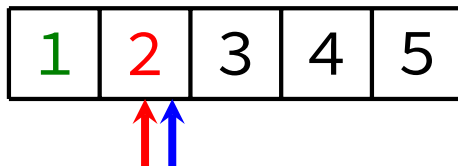
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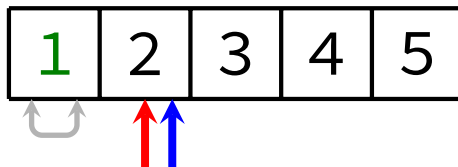
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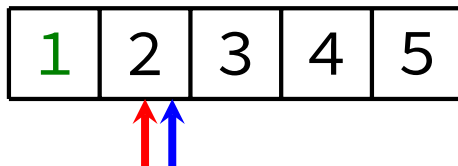
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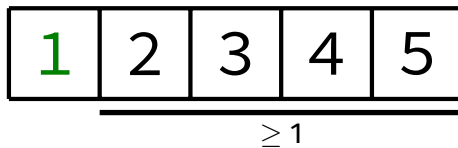
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- Partitioning is  $O(n)$ , where  $n$  is the number of elements being partitioned
  - About  $n$  comparisons are performed, at most  $\frac{n}{2}$  swaps are performed

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```
void naiveQuickSort(Item items[], int lo, int hi) {  
    if (lo >= hi) return;  
    int pivotIndex = partition(items, lo, hi);  
    naiveQuickSort(items, lo, pivotIndex - 1);  
    naiveQuickSort(items, pivotIndex + 1, hi);  
}
```



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## Quick Sort

## Method

## Partitioning

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## Analysis

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## Partitioning

## Randomised

## Partitioning

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## Sorting Lists

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```
int partition(Item items[], int lo, int hi) {
    Item pivot = items[lo];

    int l = lo + 1;
    int r = hi;
    while (l < r) {
        while (l < r && le(items[l], pivot)) l++;
        while (l < r && ge(items[r], pivot)) r--;
        if (l == r) break;
        swap(items, l, r);
    }

    if (lt(pivot, items[l])) l--;
    swap(items, lo, l);
    return l;
}
```

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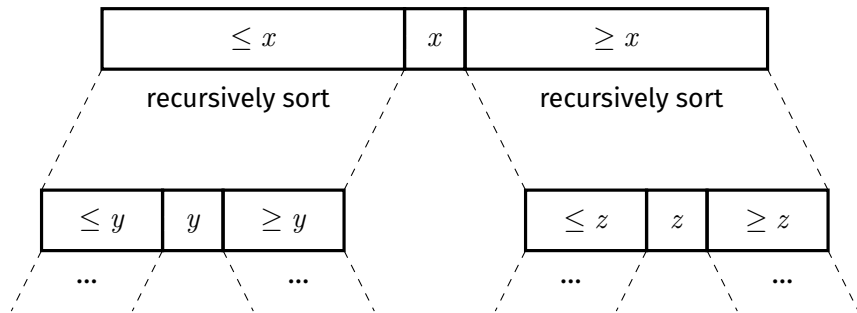
Sorting Lists

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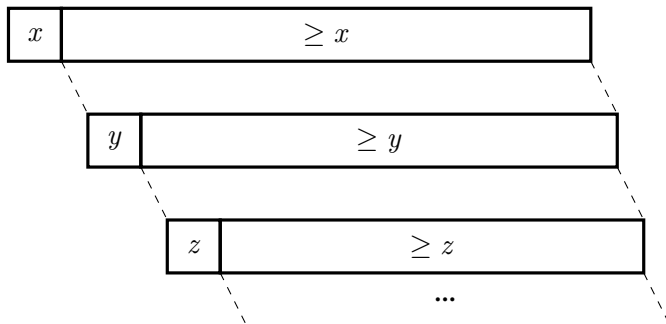
Best case:  $O(n \log n)$ 

- Choice of pivot gives two equal-sized partitions
- Same happens at every recursive call
  - Resulting in  $\log_2 n$  recursive levels
- Each “level” requires approximately  $n$  comparisons



Worst case:  $O(n^2)$

- Always choose lowest/highest value for pivot
  - Resulting in partitions of size 0 and  $n - 1$
  - Resulting in  $n$  recursive levels
- Each “level” requires one less comparison than the level above



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Average case:  $O(n \log n)$

- If array is randomly ordered, chance of repeatedly choosing a bad pivot is very low
- Can also show empirically by generating random sequences and sorting them

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**Unstable**

Due to long-range swaps

**Non-adaptive** $O(n \log n)$  average case, sorted input does not improve this**In-place**

Partitioning is done in-place

Stack depth is  $O(n)$  worst-case,  $O(\log n)$  average

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Choice of pivot can have a significant effect:

- Ideal pivot is the median value
- Always choosing largest/smallest  $\Rightarrow$  worst case

Therefore, always picking the first or last element as pivot is not a good idea:

- Existing order is a worst case
- Existing reverse order is a worst case
- Will result in partitions of size  $n - 1$  and  $0$
- This pivot selection strategy is called naïve quick sort

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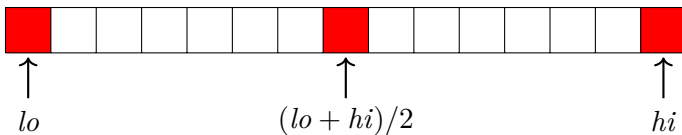
Sorting Lists

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Summary

Pick three values: left-most, middle, right-most.  
Pick the median of these three values as our pivot.

Ordered data is no longer a worst-case scenario.  
In general, doesn't eliminate the worst-case ...  
... but makes it much less likely.



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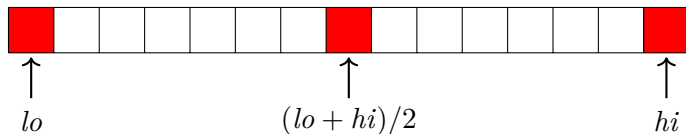
Median-of-Three  
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- 1 Sort  $a[lo]$ ,  $a[(lo + hi)/2]$ ,  $a[hi]$ , such that  $a[(lo + hi)/2] \leq a[lo] \leq a[hi]$
- 2 Partition on  $a[lo]$  to  $a[hi]$



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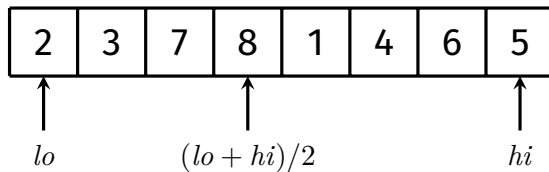
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Which element is selected as the pivot?



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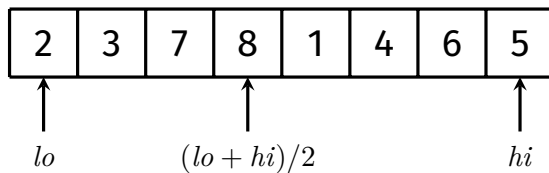
Improvements

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Answer: 5



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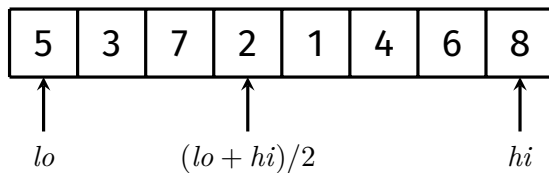
Median-of-Three  
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```
void medianOfThreeQuickSort(Item items[], int lo, int hi) {  
    if (lo >= hi) return;  
    medianOfThree(items, lo, hi);  
    int pivotIndex = partition(items, lo, hi);  
    medianOfThreeQuickSort(items, lo, pivotIndex - 1);  
    medianOfThreeQuickSort(items, pivotIndex + 1, hi);  
}
```

```
void medianOfThree(Item a[], int lo, int hi) {  
    int mid = (lo + hi) / 2;  
    if (gt(a[mid], a[lo])) swap(a, mid, lo);  
    if (gt(a[lo], a[hi])) swap(a, lo, hi);  
    if (gt(a[mid], a[lo])) swap(a, mid, lo);  
    // now, we have a[mid] <= a[lo] <= a[hi]  
}
```

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**Randomised  
Partitioning**

Improvements

Sorting Lists

Comparison

Summary

Idea: Pick a random value for the pivot

This makes it *nearly* impossible to  
systematically generate inputs that would lead to  
 $O(n^2)$  performance

Merge Sort

Quick Sort

Method

Partitioning

Implementation

Analysis

Properties

Issues

Median-of-Three

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```
void randomisedQuickSort(Item items[], int lo, int hi) {
    if (lo >= hi) return;
    swap(items, lo, randint(lo, hi));
    int pivotIndex = partition(items, lo, hi);
    randomisedQuickSort(items, lo, pivotIndex - 1);
    randomisedQuickSort(items, pivotIndex + 1, hi);
}

int randint(int lo, int hi) {
    int i = rand() % (hi - lo + 1);
    return lo + i;
}
```

Note: `rand()` is a pseudo-random number generator provided by `<stdlib.h>`.  
The generator should be initialised with `srand()`.

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For small sequences (when  $n < 5$ , say),  
quick sort is **expensive**  
because of the recursion overhead.

Solution: Handle small partitions with insertion sort

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```
#define THRESHOLD 5

void quickSort(Item items[], int lo, int hi) {
    if (hi - lo < THRESHOLD) {
        insertionSort(items, lo, hi);
        return;
    }

    medianOfThree(items, lo, hi);
    int pivotIndex = partition(items, lo, hi);
    quickSort(items, lo, pivotIndex - 1);
    quickSort(items, pivotIndex + 1, hi);
}
```



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```
#define THRESHOLD 5
```

```
void quickSort(Item items[], int lo, int hi) {  
    doQuickSort(items, lo, hi);  
    insertionSort(items, lo, hi);  
}
```

```
void doQuickSort(Item items[], int lo, int hi) {  
    if (hi - lo < THRESHOLD) return;  
  
    medianOfThree(items, lo, hi);  
    int pivotIndex = partition(items, lo, hi);  
    doQuickSort(items, lo, pivotIndex - 1);  
    doQuickSort(items, pivotIndex + 1, hi);  
}
```

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It is possible to quick sort a linked list:

- 1 Pick first element as pivot
  - Note that this means ordered data is a worst case again
  - Instead, can use median-of-three or random pivot
- 2 Create two empty linked lists  $A$  and  $B$
- 3 For each element in original list (excluding pivot):
  - If element is less than (or equal to) pivot, add it to  $A$
  - If element is greater than pivot, add it to  $B$
- 4 Recursively sort  $A$  and  $B$
- 5 Form sorted linked list using sorted  $A$ , the pivot, and then sorted  $B$

Merge Sort

Quick Sort

Comparison

Summary

Design of modern CPUs mean,  
for sorting arrays in RAM  
quick sort *generally* outperforms merge sort.

Quick sort is more 'cache friendly':  
good locality of access on arrays.

On the other hand, merge sort is  
readily stable, readily parallel,  
a good choice for sorting linked lists

Merge Sort

Quick Sort

Comparison

Summary

	Time complexity			Properties	
	Best	Average	Worst	Stable	Adaptive
Merge sort	$O(n \log n)$	$O(n \log n)$	$O(n \log n)$	Yes	No
Quick sort	$O(n \log n)$	$O(n \log n)$	$O(n^2)$	No	No

Merge Sort

Quick Sort

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<https://forms.office.com/r/5c0fb4tvMb>

