Lecture 3: Sorting Algorithms

Bo Tang @ SUSTech, Fall 2022

Sorting Problem

- Sorting problem
  - Input: an array A[1..n] with n integers
  - Output: a sorted array A (in ascending order)

- Problem is: sort A[1..n]
- Input: | 8 | 6 | 1 | 3 | 7 | 2 | 5 | 4 |
- Output: | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |

comparison-based sorting: insertion, bubble, selection, quick, heap, shell

other sorting: radix, bucket

Our Roadmap

- Comparison-based Sorting
  - Quadratic Cost $O(n^2)$
    - Selection Sort, Insertion Sort, Bubble Sort
  - O(n log n) Cost
    - Merge Sort, Heap Sort (we will skip here)
  - Quick Sort $\begin{cases} O(n^2) \\ O(n \log n) \end{cases}$
- Other sorting algorithms
  - Counting sort, radix sort, bucket sort

Selection Sort

Selection Sort

- Idea of a selection sort method
  - Start with empty hand, all cards on table
  - Pick the smallest card from table
  - Insert the card into the hand

	8
	5
	2
	6
	9
	3
	1
	4
	0
	7

Selection Sort Algorithm

pseudocode

- SelectionSort
  - Input: an **array** A of n numbers
  - Output : an **array** A of n numbers in the <u>ascending order</u>
  - Selection-Sort ($A[1..n]$)

```
for integer i ← 1 to n–1
    k ← i
    for integer j ← i+1 to n
        if  A[k] > A[j]  then
            k ← j
    swap A[i] and A[k]
```

k stores the index of the smallest

8 | 6 | 1 | 3 | 7 | 2 | 5 | 4

1 | 6 | 8 | 3 | 7 | 2 | 5 | 4

sorted *unsorted*

1 | 2 | 8 | 3 | 7 | 6 | 5 | 4

sorted *unsorted*

Selection Sort Time Complexity

- Selection Sort
  - Input: an **array** A of n numbers
  - Output : an **array** A of n numbers in the ascending order

    $\exists\, c_1 > 0 .\ f(n) \le c_1 \cdot g(n)$ for $n \ge c_2$
  - Selection-Sort ($A[1..n]$)

1. for integer $i \leftarrow 1$ to $n-1$	Cost: n-1=O(n)
2. $\quad k \leftarrow i$	Cost: n-1=O(n)
3. $\quad$ for integer $j \leftarrow i+1$ to n	Cost: n-1+n-2+…+1=O(n^2)
4. $\quad\quad$ if $A[k] > A[j]$ then	Cost: O(n^2)
5. $\quad\quad\quad k \leftarrow j$	Cost: O(n^2)
6. $\quad$ swap $A[i]$ and $A[k]$	Cost: O(n)

$\Longrightarrow$ cost : $\frac{3}{2}n^2 + \frac{3}{2}n - 3$ （用算子来算）

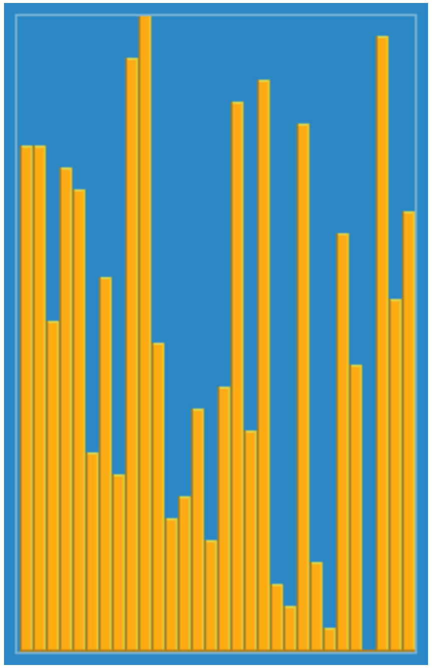
- Selection sort total cost:
- O(n)+O(n)+O(n^2) +O(n^2) +O(n^2) +O(n)=O(n^2)

Insertion Sort

Insertion Sort

- Idea of a insertion sort method
  - One input each iteration, growing a sorted output list
  - Remove one element from input data
  - Find the location it belongs within the sorted list
  - Repeat until no input elements remain

6 5 3 1 8 7 2 4



Insertion Sort Algorithm

- InsertionSort
  - Input: an **array** A of n numbers
  - Output : an **array** A of n numbers in the ascending order
  - Insertion-Sort ($A[1..n]$)

```
for integer i ← 1 to n
    for integer j ← i to 1 with j > 1
        if  A[j-1] > A[j]  then
            swap A[j-1] and A[j]
        else  break
```

NOT j>0

8 | 6 | 1 | 3 | 7 | 2 | 5 | 4

sorted *unsorted*

8 | 6 | 1 | 3 | 7 | 2 | 5 | 4

6 | 8 | 1 | 3 | 7 | 2 | 5 | 4

sorted *unsorted*

1 | 6 | 8 | 3 | 7 | 2 | 5 | 4

Insertion Sort Time Complexity

- Insertion Sort
  - Input: an **array** *A* of *n* numbers
  - Output : an **array** *A* of *n* numbers in the ascending order
  - Insertion-Sort (*A*[1..*n*])

1. for integer $i \leftarrow 1$ to n — Cost: $n-1=O(n)$
2. for integer $j \leftarrow i$ *to 1 with* $j > 1$ — Cost: $1+\ldots+n-2=O(n^2)$
3. if $A[j-1] > A[j]$ then — Cost: $O(n^2)$
4. swap $A[j-1]$ and $A[j]$ — Cost: $O(n^2)$
5. else break

- Insertion sort total cost:
  - $O(n)+O(n^2)+O(n^2)+O(n^2)=O(n^2)$

Bubble Sort

Bubble Sort

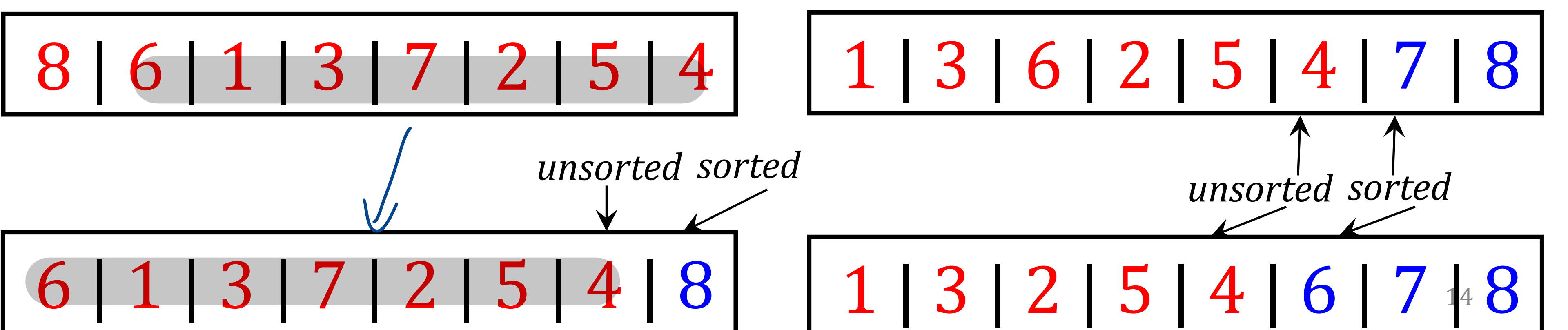
- Idea of a bubble sort method
  - For each pass
    - Compare the pair of adjacent item
    - Swap them if they are in the wrong order
  - Repeat the pass through until no swaps are needed

6 5 3 1 8 7 2 4

Bubble Sort Algorithm

- BubbleSort (optimized version)
  - Input: an **array** *A* of *n* numbers
  - Output : an **array** *A* of *n* numbers in the <u>ascending order</u>
  - Bubble-Sort (*A*[1..*n*])

```
for integer i ← 1 to n–1
    for integer j ← 2 to n
        if  A[j-1] > A[j]  then
            swap A[j-1] and A[j]
```



Bubble Sort Time Complexity

- Bubble Sort
  - Input: an **array** A of n numbers
  - Output : an **array** A of n numbers in the <u>ascending order</u>
  - Bubble-Sort ($A[1..n]$)

    1. for integer $i \leftarrow 1$ to $n-1$ — Cost: n-1=O(n)
    2. for integer $j \leftarrow 2$ to n — Cost: n-1+…+n-1=O(n^2)
    3. if $A[j\text{-}1] > A[j]$ then — Cost: O(n^2)
    4. swap $A[j\text{-}1]$ and $A[j]$ — Cost: O(n^2)
- Bubble sort total cost:
  - $O(n)+O(n^2) +O(n^2) +O(n^2) =O(n^2)$

Pop Quiz

- We say a sorting algorithm is "stable" if it does not change the relative order of elements with equal keys, which of the following is/are stable ()

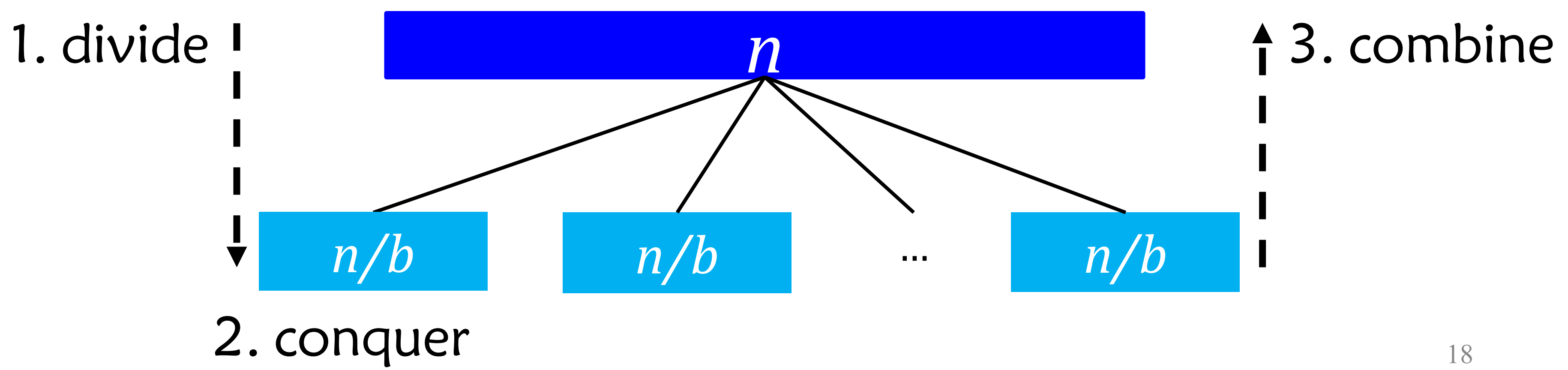
  A: Selection sort B: Insertion Sort C: Bubble Sort

- Watch a video:
  - 1) Which sorting algorithm is used in that video?
  - 2) TB is No. x, so x = ?

Merge Sort
(Divide-and-Conquer)

Divide and Conquer 分治

- Divide and Conquer: an algorithmic technique
  - ① **Divide:** divide the problem into smaller subproblems
  - ② **Conquer:** solve each subproblem recursively
  - ③ **Combine:** combine the solution of subproblems into the solution of the original problem



Example: Merge Sort

- Sorting problem
  - Input: an array $A[1..n]$ with n integers
  - Output: a sorted array A (in ascending order)

- Original problem is: sort $A[1..n]$

| 8 | 6 | 1 | 3 | 7 | 2 | 5 | 4 |

- What is a subproblem?
  - Sort a subarray $A[l..r]$

| 7 | 2 | 5 | 4 |

Merge Sort

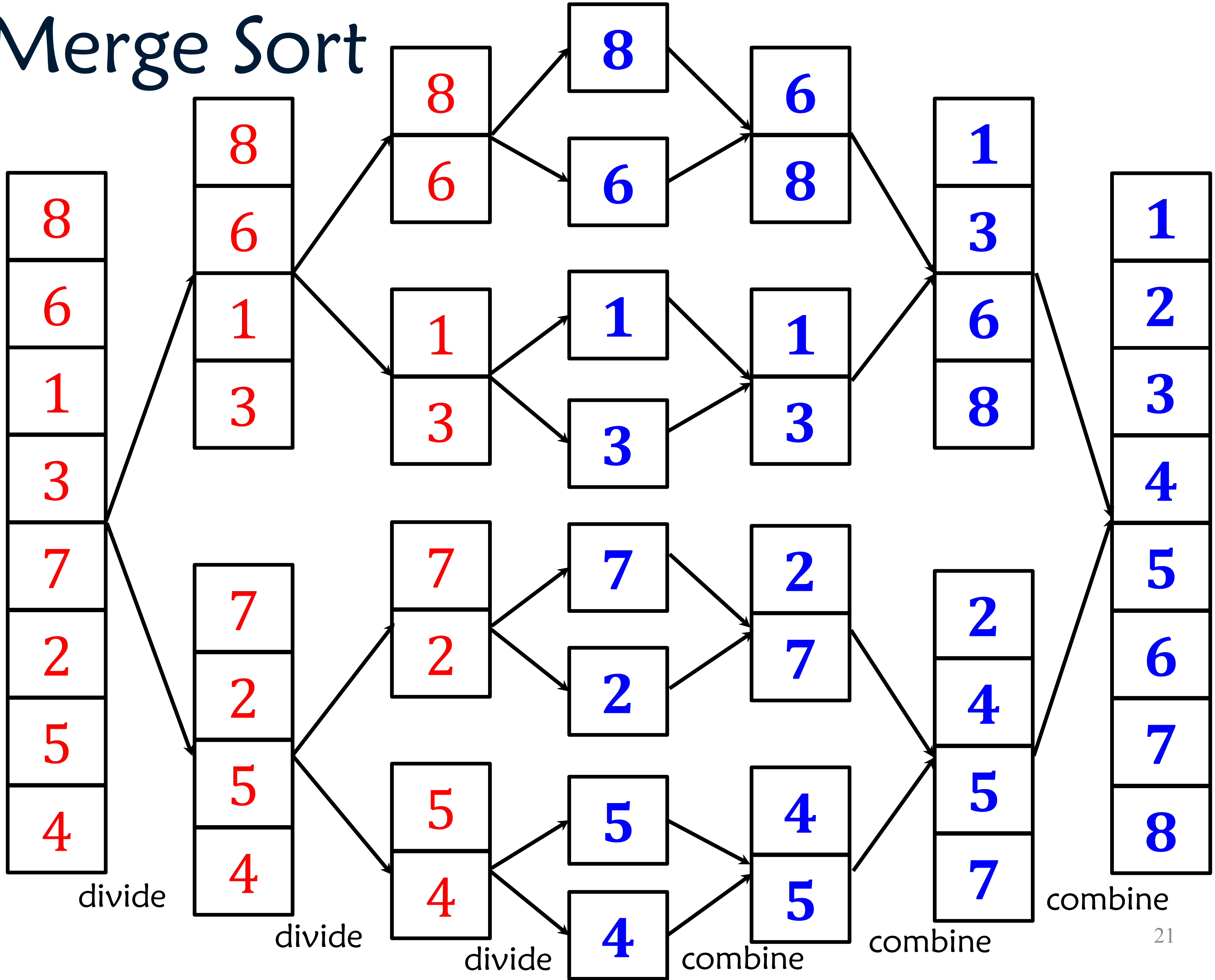
- Merge Sort
  - **Divide**: divide the array into two subarrays of n/2 numbers each
  - **Conquer**: sort two subarrays recursively
  - **Combine**: merge two sorted subarrays into a sorted array

Merge-Sort(A, n)

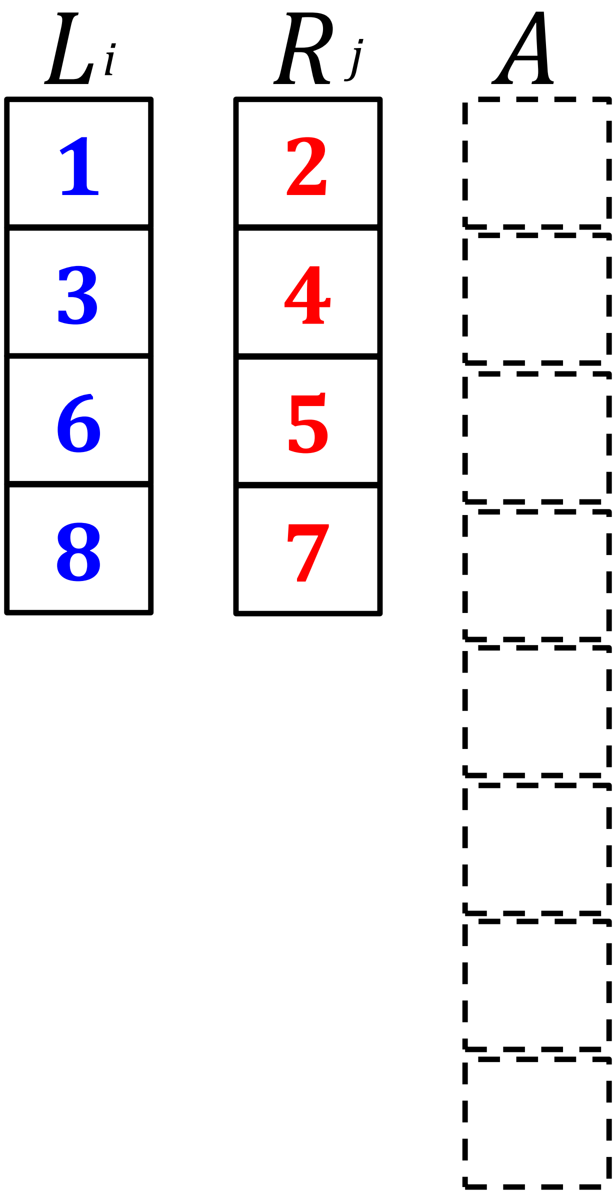
1. if $n > 1$
2. $p \leftarrow \lfloor n/2 \rfloor$
3. $B[1..p] \leftarrow A[1..p]$
4. $C[1..n\text{-}p] \leftarrow A[p+1..n]$
5. Merge-Sort(B, p)
6. Merge-Sort(C, n-p)
7. $A[1..n] \leftarrow$ Merge(B, p, C, n-p)

We'll discuss the Combine phase ("Merge" function) later

Merge Sort


8
6
1
3
7
2
5
4
divide
8
6
1
3
7
2
5
4
divide
8
6
1
3
7
2
5
4
divide
8
6
1
3
7
2
5
4
combine
6
8
1
3
2
7
4
5
combine
1
3
6
8
2
4
5
7
combine
1
2
3
4
5
6
7
8

Merge Sort: Combine Phase



Sorted arrays

Merge(L, n_L, R, n_R)

1. n ← $n_L + n_R$
2. let A[1..n] be a new array
3. i ← 1; j ← 1
4. for k ← 1 to n
5.   if $i \leq n_L$ and ($j > n_R$ *or* $L[i] \leq R[j]$)
6.   A[k] ← $L[i]$; i ← $i + 1$
7.   else
8.   A[k] ← $R[j]$; j ← $j + 1$
9. return A

Running time of Merge

Sorted arrays

Merge(L, n_L, R, n_R)

1. n ← $n_L + n_R$
2. let A[1..n] be a new array
3. i ← 1; j ← 1
4. for k ← 1 to n
5.   if $i \le n_L$ and ($j > n_R$ *or* $L[i] \le R[j]$)
6.   A[k] ← $L[i]$; i ← $i + 1$
7.   else
8.   A[k] ← $R[j]$; j ← $j + 1$
9. return A

- Let $n = n_L + n_R$ be the total number of items
- Time of merge: O(n) time
  - Line 1: O(1)
  - Line 2: O(n)
  - Line 3: O(1)
  - Lines 4-8: O(n)

Running time of Merge Sort

Merge-Sort(A, n)

1. if $n > 1$
2. $p \leftarrow \lfloor n/2 \rfloor$
3. $B[1..p] \leftarrow A[1..p]$
4. $C[1..n\text{-}p] \leftarrow A[p+1..n]$
5. Merge-Sort(B, p)
6. Merge-Sort(C, n-p)
7. $A[1..n] \leftarrow$ Merge(B, p, C, n-p)

- Let $T(n)$ be the running time of Merge Sort
  - Lines 3, 4 take $O(n)$ time
  - Line 5 takes $T(n/2)$ time
  - Line 6 takes $T(n/2)$ time
  - Line 7 takes $O(n)$ time
- Thus, we obtain the recurrence

$$T(n) = 2\,T(n/2) + O(n)$$

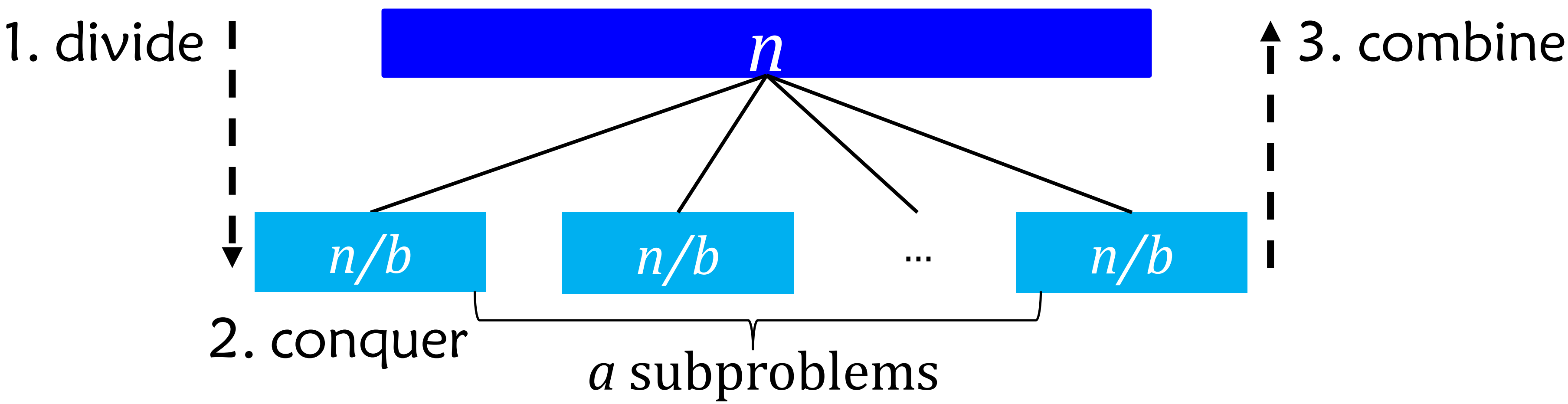
- Solving it, we get:

$$T(n) = O(n\log n)$$

Time Complexity

- T(n): time complexity of algorithm at input size n
  - Divide the problem into a subproblems
  - Size of each subproblem is n/b
  - Combine phase takes $f(n)$ time

Note: a and b can have different values



- Recurrence equation: $T(n) = a\,T(n/b) + f(n)$
- E.g., Merge Sort: $T(n) = 2\,T(n/2) + O(n)$

Methods for Solving Recurrences

- Recurrence equation: $T(n) = a\,T(n/b) + f(n)$
- Two methods for solving recurrences
  - Master theorem
  - Substitution method

③ Recursion Tree method

①
- Master theorem
  - It could be proved by carefully applying the "expansion method", the details are tedious and omitted from this course

②
- Substitution method (we skip it here)
  - It is mathematical induction

Master Theorem

- Recurrence equation: T(n) = a T(n/b) + f(n)
- Let T(n) be a function that return a positive value for every integer n>0. We know that:
  - $T(1) = O(1)$
  - $T(n) = \alpha T\left(\left\lceil \frac{n}{\beta} \right\rceil\right) + O(n^{\gamma})$ for (n ≥ 2)

  where $\alpha \geq 1, \beta > 1,$ and $\gamma \geq 0$. Then:
  - If $\log_{\beta} \alpha < \gamma$, then $T(n) = O(n^{\gamma})$
  - If $\log_{\beta} \alpha = \gamma$, then $T(n) = O(n^{\gamma} \log n)$
  - If $\log_{\beta} \alpha > \gamma$, then $T(n) = O(n^{\log_{\beta} \alpha})$

Master Theorem

Lawrence Chiou, Agnishom Chattopadhyay, Geoff Pilling, and 4 others contributed

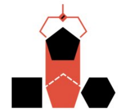
The **master theorem** provides a solution to recurrence relations of the form

$$T(n) = aT\left(\frac{n}{b}\right) + f(n),$$

for constants $a \geq 1$ and $b > 1$ with f asymptotically positive. Such recurrences occur frequently in the runtime analysis of many commonly encountered algorithms.

Recommended Course

Algorithms (2019)



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Relevant For...

Computer Science > Complexity / Runtime Analysis

Computer Science > Dynamic Programming

Contents

Introduction

Many algorithms have a ru...

Master Theorem

- Consider the recurrence of **binary search**:
  - $T(1) \le c1$
  - $T(n) \le T(n/2) + c2$ (for $n \ge 2$)
  - Hence, $\alpha = 1$, $\beta = 2$, and $\gamma = 0$. Since $\log_\beta \alpha = \log_2 1 = 0 = \gamma$, we know that $T(n) = O(n^0 \log n) = O(\log n)$.

$T(n) = T(\frac{n}{2}) + O(1)$

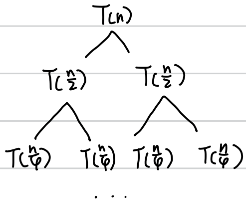
- Consider the recurrence of **merge sort**:
  - $T(1) \le c1$
  - $T(n) = 2\,T(n/2) + O(n) = 2\,T(n/2) + c2\,n$ (for $n \ge 2$)
  - Hence, $\alpha = 2$, $\beta = 2$, and $\gamma = 1$. Since $\log_\beta \alpha = \log_2 2 = 1 = \gamma$, we know that $T(n) = O(n^1 \log n) = O(n\log n)$.

$T(n) = 2 \cdot T(\frac{n}{2}) + O(n)$

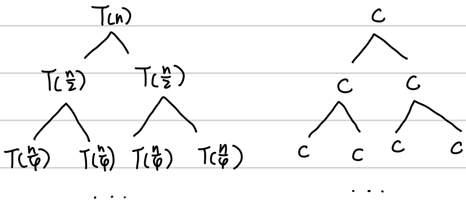
Recursion Tree Method

eg. 1 $T(n) = 2T(\frac{n}{2}) + c$

① draw a recursive tree



② calculate the cost at each level



③ count total number of nodes in the last level
and calculate cost of last level

$\ast$ last level $\Longrightarrow$ the size of problem become 1 (the base case)

$(\frac{1}{2})^x \cdot n = 1 \Longrightarrow x = \log_{\frac{1}{2}}^{n} = \log^{n}$

$\Longrightarrow T(n)$ has $x = \log_{\frac{1}{2}}^{n}$ levels.

④ Sum up the cost all the levels in recursive tree

As $S(n) = a_1 \frac{1-q^n}{1-q}$ for $a_n = a_1 \cdot q^{n-1}$

$\Rightarrow T(n) = c \cdot \frac{1-2^n}{1-2}$

As $x = \log_{\frac{1}{2}}^{n}$

$T(n) = c \cdot \frac{1-2^{\log_{\frac{1}{2}}^{n}}}{1-2}$

$\log_{\frac{1}{2}}^{n} = \log_2^{-n}$

$T(n) = c \cdot \frac{1-(-n)}{1-2}$

$=$

Quick Sort
RAM with Randomization

eg. unsorted A.

find the ith least

solve: find a number.

Deterministic & Randomized

- So far in CS203, all our algorithms are deterministic, namely, they do not involve any randomization.
- We will introduce randomized algorithms, e.g., quick sort in the sorting problem.
- Randomized algorithms play an important role in computer science, they often simpler, and sometimes can be provably faster as well.
- Recall the core of the RAM model is a set of atomic operations, we extend this set with:
  - RANDOM(x, y): given integers x and y (x <= y), this operation returns an integer chosen uniformly at random in [x,y], i.e., x, x+1, ..., y has the same probability of being returned.

Deterministic & Randomized

Operator

A mapping of one set into another, each of which has a certain structure (defined by algebraic operations, a topology, or by an order relation). The general definition of an operator coincides with the definition of a mapping or function. Let X and Y be two sets. A rule or correspondence which assigns a uniquely defined element $A(x) \in Y$ to every element x of a subset $D \subset X$ is called an operator A from X into Y.

$$A : D \to Y, \qquad \text{where } D \subset X. \tag{1}$$

The term operator is mostly used in the case where X and Y are vector spaces. The expression $A(x)$ is often written as Ax.

computer science, they often simpler, and sometimes can be provably faster as well.

- Recall the core of the RAM model is a set of atomic operations, we extend this set with:
  - RANDOM(x, y): given integers x and y (x <= y), this operation returns an integer chosen uniformly at random in [x,y], i.e., x, x+1, …, y has the same probability of being returned.

Randomized Algorithm Example

- Find-a-Zero: Given an array of integers with size n, among which there is at least 0. Design an algorithm to report an arbitrary position of A that contains a 0
- Suppose A = (9,18,0,0,15,0), an algorithm can report 3,4 or 6, consider the following randomized algorithm
- 1. do
- 2. r ← RANDOM(1,n)
- 3. until A[r]=0
- 4. return r
- What is the cost of the algorithm? It depends
  - If all numbers in A are 0, O(1) time. If A has only one 0, O(n) expected time.
  - As before, we care about the worst expected time: O(n)

Quick Sort

- Idea of a quick sort method
  - Randomly pick an integer p in A, call it the pivot
  - Re-arrange the integers in an array A' such that
    - All the integers smaller than p are positioned before p in A'
    - All the integers larger than p are positioned after p in A'
  - Sort the part of A' before p recursively
  - Sort the part of A' after p recursively

Quicksort

- Quick Sort
  - Input: an **array** A of n numbers
  - Output : an **array** A of n numbers in the <u>ascending order</u>
  - Quicksort ($A[1..n]$, lo=1, hi=n)
    1. p ← partition(A, lo, hi)
    2. Quicksort(A,lo,p-1)
    3. Quicksort(A,p+1,hi)

Quicksort

- Partition(A, lo, hi)

```
1. p ← RANDOM(lo, hi);  pivot ← A[p];
2. L ← lo, R← hi
3. for integer i from lo to hi
4.        if(i!=p)
5.               if(A[i] < pivot) A'[L++]←A[i]
6.               else A'[R--]←A[i]
7. A'[L] ← pivot
8. A[lo, hi] ← A'
9. return L;
```

- Question:
  - If we set p ← lo or hi in Line 1, quick sort is still correct ?
  - What are the difference between p ← lo/hi and p ← RANDOM(lo, hi)?

Quicksort Example

8 | 6 | 1 | 3 | 7 | 2 | 5 | 4

pivot

1 | 3 | 2 | 5 | 4 | 6 | 7 | 8

pivot

1 | 2 | 3 | 4 | 5 | 6 | 7 | 8

pivot *pivot* *pivot*

1 | 2 | 3 | 4 | 5 | 6 | 7 | 8

pivot *pivot* *pivot* *pivot* *pivot*

Quicksort Time Complexity

always choose the boundary

- Quicksort's running time is not attractive in the worst case: it is $O(n^2)$ (why?) However, quick sort is fast in expectation, i.e., O(nlogn), remember this holds for every input array A.

~~P= high~~
~~P= low~~
P= RANDOM

not need to combine

- Whether quicksort has any advantage over merge sort? which guarantees O(nlogn) in the worst case.
- No in theory, but there is an advantage in practice
- Quicksort permits a faster implementation that leads to a smaller hidden constant compared to merge sort. (why?)

prove: $E(T(n)) = O(n\log n)$

① comparison ×
② swapping ×

all sorts need comparison
have 2 steps

Quicksort Time Complexity

- Let X be the number of comparisons in quicksort algorithm. The running is bounded by O(n+x).

→ 任意2个元素比较 ⇒ 选了 j/i

- We prove that E[X]=O(n log n)
- Denote e_i be the i-th smallest integer in A, consider e_i and e_j for any i,j such that i!=j
- What is the probability that quicksort compares e_i and e_j?
  - Every element will be selected as pivot precisely once
  - e_i and e_j are not compared, if any element between them gets selected as a pivot before them.
  - Therefore, e_i and e_j are compared if and only if either one is the first among e_i , e_{i+1} ,..., e_j picked as a pivot
  - The probability is 2/(j-i+1) (random pivot selection)

Quicksort Time Complexity

- Define random variable X_{ij} to be 1, if e_i and e_j are compared. Otherwise, X_{ij} to be 0. Thus, we have
- $Pr[X_{ij} = 1] = 2/(j-i+1)$, that is $E[X_{ij}] = 2/(j-i+1)$
- Since $X = \sum_{i,j} X_{ij}$, hence:
- $E[X] = \sum_{i,j} E[X_{ij}] = \sum_{i,j} \frac{2}{j-i+1}$
- $= 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{1}{j-i+1}$ harmonic series
- $= 2 \sum_{i=1}^{n-1} O(\log(j-i+1))$ $(1+1/2+\ldots+1/n = O(\log n))$
- $= 2 \sum_{i=1}^{n-1} O(\log n)$
- $= O(n \log n)$
- Harmonic series: $1+1/2+\ldots+1/n$, which is frequently encountered in computer science.

Summary

Sort	Average	Space
Selection	$O(n^2)$	$O(1)$
Insertion	$O(n^2)$	$O(1)$
Bubble	$O(n^2)$	$O(1)$
Heap	$O(n\log n)$	$O(1)$
Merge	$O(n\log n)$	Depends
Quick	$O(n\log n)$	$O(1)$

- Comparison lower bound of sorting algorithm: $\Omega(n \log n)$
- We omit the proof here.

Other Sorting Methods

Other Sorting Algorithms

- Counting sort (Chapter 8.2)
  - it is applicable when each input is known to belong to a particular set, S, of possibilities. The algorithm runs in $O(|S| + n)$ time and $O(|S|)$ memory where n is the length of the input.
- Radix sort (Chapter 8.3)
  - radix sort is an algorithm that sorts numbers by processing individual digits. n numbers consisting of k digits each are sorted in $O(n \cdot k)$ time
- Bucket sort (Chapter 8.4)
  - Bucket sort is a divide and conquer sorting algorithm that generalizes counting sort by partitioning an array into a finite number of buckets.

Thank You!