Special Cases of the Sorting Problem

In this lecture we assume that the sort keys are sequences of bits.

- Quite a natural special case. Doesn’t cover everything:
  - e.g., exact real number arithmetic doesn’t take this form.
  - In certain applications, e.g. in Biology, pairwise experiments may only return $>$ or $<$ (non-numeric).
- Sometimes the bits are naturally grouped, e.g. as characters in a string or hexadecimal digits in a number (4 bits), or in general bytes (8 bits).
- Today’s sorting algorithms are allowed access these bits or groups of bits, instead of just letting them compare keys . . .
  This was NOT possible in comparison-based setting.

Easy results . . . Surprising results

Simplest Case:
Keys are integers in the range 1, . . . , $m$, where $m = O(n)$ ($n$ is (as usual) the number of elements to be sorted). We can sort in $\Theta(n)$ time.

Surprising case: (I think)
For any constant $k$, the problem of sorting $n$ integers in the range $\{1, \ldots, nk\}$ can be done in $\Theta(n)$ time.
Easy results … Surprising results

Simplest Case:
Keys are integers in the range 1, . . . , m, where m = O(n) (n is as usual the number of elements to be sorted). We can sort in Θ(n) time (big deal … but will help later).

Surprising case: (I think)
For any constant k, the problem of sorting n integers in the range 1, . . . , nk can be done in Θ(n) time.

Counting Sort
Assumption: Keys (attached to items) are Integers in range 1, . . . , m.

Idea
1. Count for every key j, 1 ≤ j ≤ m how often it occurs in the input array. Store results in an array C.

2. The counting information stored in C can be used to determine the position of each element in the sorted array. Suppose we modify the values of the C[j] so that now C[j] = the number of keys less than or equal to j. Then we know that the elements with key "j" must be stored at the indices C[j − 1] + 1, . . . , C[j] of the final sorted array.

3. We use a "trick" to move the elements to the right position of an auxiliary array. Then we copy the sorted auxiliary array back to the original one.
Counting Sort

Assumption: Keys (attached to items) are Integers in range 1, \ldots, m.

Idea

1. Count for every key $j$, $1 \leq j \leq m$ how often it occurs in the input array. Store results in an array $C$.
2. The counting information stored in $C$ can be used to determine the position of each element in the sorted array. Suppose we modify the values of the $C[j]$ so that now $C[j] =$ the number of keys less than or equal to $j$.

Then we know that the elements with key "$j$" must be stored at the indices $C[j - 1] + 1, \ldots, C[j]$ of the final sorted array.

Algorithm Counting Sort($A, m$)

1. $n \leftarrow A.length$
2. Initialise array $C[1 \ldots m]$
3. for $i \leftarrow 1$ to $n$ do
   4. $j \leftarrow A[i].key$
   5. $C[j] \leftarrow C[j] + 1$
6. for $j \leftarrow 2$ to $m$ do
7. $C[j] \leftarrow C[j] + C[j - 1]$ \Comment{$C[j]$ stores \# of keys \leq j}
8. Initialise array $B[1 \ldots n]$
9. for $i \leftarrow n$ downto 1 do
10. $j \leftarrow A[i].key$ \Comment{$A[i]$ highest w. key $j$}
11. $B[C[j]] \leftarrow A[i]$ \Comment{Insert $A[i]$ into highest free index for $j$}
12. $C[j] \leftarrow C[j] - 1$
13. for $i \leftarrow 1$ to $n$ do

Analysis of Counting Sort

- The loops in lines 3–5, 9–12, and 13–14 all require time $\Theta(n)$.
- The loop in lines 6–7 requires time $\Theta(m)$.
- Thus the overall running time is

$$O(n + m).$$

- This is linear in the number of elements if $m = O(n)$. 

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Analysis of Counting Sort

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- Thus the overall running time is
  
  \[ O(n + m) \] 

- This is linear in the number of elements if \( m = O(n) \).

Note: This does not contradict Theorem 3 from Lecture 7 - that’s a result about the general case, where keys have an arbitrary size (and need not even be numeric).

Counting-Sort is STABLE.

- (After sorting, 2 items with the same key have their initial relative order).

Radix Sort

Basic Assumption

Keys are sequences of digits in a fixed range 0, ..., \( R - 1 \), all of equal length \( d \).

Examples of such keys

- 4 digit hexadecimal numbers (corresponding to 16 bit integers)
  
  \( R = 16, d = 4 \)

- 5 digit decimal numbers (for example, US post codes)
  
  \( R = 10, d = 5 \)

- Fixed length ASCII character sequences
  
  \( R = 128 \)

- Fixed length byte sequences
  
  \( R = 256 \)

Stable Sorting Algorithms

Definition 1

A sorting algorithm is stable if it always leaves elements with equal keys in their original order.
Stable Sorting Algorithms

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A sorting algorithm is **stable** if it always leaves elements with equal keys in their original order.

Examples
- **Counting-Sort**, **Merge-Sort**, and **Insertion Sort** are all stable.
- **Quicksort** is not stable.

Radix Sort (cont’d)

Idea
Sort the keys digit by digit, **starting with the least significant digit**.

Example
```
now sob tag ace
for nob ace bet
tip aca bet dim
ilk tag dim for
dim ilk tip hut
tag dim sky ilk
jot tip ilk jot
sob for sob nob
nob jot nob now
sky hut for sky
hut bet jot sob
ace now now tag
bet sky hut tip
```

Each of the three sorts is carried out with respect to the digits in that column. “Stability” (and having previously sorted digits/suffixes to the right), means this achieves a sorting of the suffixes starting at the current column.

Sorting Integers with Radix-Sort

Theorem 2
An array of length \(n\) whose keys are \(b\)-bit numbers can be sorted in time
\[
\Theta(n\lceil b/\log n \rceil)
\]
using a suitable version of **Radix-Sort**.

Proof: Let the digits be blocks of \([\log n]\) bits. Then \(R = 2^{\lceil \log n \rceil} = \Theta(n)\) and \(d = \lceil b/\log n \rceil\). Using the implementation of **Radix-Sort** based on **Counting Sort** the integers can be sorted in time
\[
\Theta(d(n + R)) = \Theta(n\lceil b/\log n \rceil).
\]

Note: If all numbers are at most \(n^k\), then \(b = k \log n \Rightarrow \) **Radix Sort** is \(\Theta(n)\) (assuming \(k\) is some constant, e.g., 3, 10).
**Problems**

1. Think about the qn. on slide 7 - how do we get a very easy (non-stable) version of COUNTING-SORT if there are no items attached to the keys?

2. Can you come up with another way of achieving counting sort’s $O(m + n)$-time bound and stability (you will need a different data structure from an array).

3. Exercise 8.3-4 of [CLRS].

*ADS: lect 9 – slide 12 –*