

Announcements:

- We'll be running a preliminary test run for Project #2 on Monday night.

Today: Sorting, continued

- Quicksort
- Selection
- Distribution counting
- Radix sorts

Next topic readings: *Data Structures*, Chapter 9.

Idea:

- *Partition* data into pieces: everything $>$ a *pivot* value at the high end of the sequence to be sorted, and everything \leq on the low end.
- Repeat recursively on the high and low pieces.
- For speed, stop when pieces are "small enough" and do insertion sort on the whole thing.
- Reason: insertion sort has low constant factors. By design, no item will move out of its will move out of its piece [why?], so when pieces are small, #inversions is, too.
- Have to choose pivot well. E.g.: *median* of first, last and middle items of sequence.

Example of Quicksort

- In this example, we continue until pieces are size ≤ 4 .
- Pivots for next step are starred. Arrange to move pivot to dividing line each time.
- Last step is insertion sort.

16|10|13|18|-4|-7|12|-5|19|15|0|22|29|34|-1*

-4|-5|-7|-1|18|13|12|10|19|15|0|22|29|34|16*

-4|-5|-7|-1|15|13|12*|10|0|16|19*|22|29|34|18

-4|-5|-7|-1|10|0|12|15|13|16|18|19|29|34|22

- Now everything is "close to" right, so just do insertion sort:

-7|-5|-4|-1|0|10|12|13|15|16|18|19|22|29|34

Performance of Quicksort

- Probabalistic time:
 - If choice of pivots good, divide data in two each time: $\Theta(N \lg N)$ with a good constant factor relative to merge or heap sort.
 - If choice of pivots bad, most items on one side each time: $\Theta(N^2)$.
 - $\Omega(N \lg N)$ in best case, so insertion sort better for nearly ordered input sets.
- Interesting point: randomly shuffling the data before sorting makes $\Omega(N^2)$ time very unlikely!

Quick Selection

The Selection Problem: for given k , find k^{th} smallest element in data.

- Obvious method: sort, select element $\#k$, time $\Theta(N \lg N)$.
- If $k \leq$ some constant, can easily do in $\Theta(N)$ time:
 - Go through array, keep smallest k items.
- Get probably $\Theta(N)$ time for all k by adapting quicksort:
 - Partition around some pivot, p , as in quicksort, arrange that pivot ends up at dividing line.
 - Suppose that in the result, pivot is at index m , all elements \leq pivot have indices $\leq m$.
 - If $m = k$, you're done: p is answer.
 - If $m > k$, recursively select k^{th} from left half of sequence.
 - If $m < k$, recursively select $(k - m - 1)^{\text{th}}$ from right half of sequence.

Selection Example

Problem: Find just item $\#10$ in the sorted version of array:

Initial contents:

51	60	21	-4	37	4	49	10	40	59	0	13	2	39	11	46	31
0																

Looking for $\#10$ to left of pivot 40:

13	31	21	-4	37	4*	11	10	39	2	0	40	59	51	49	46	60
0																

Looking for $\#6$ to right of pivot 4:

-4	0	2	4	37	13	11	10	39	21	31*	40	59	51	49	46	60
4																

Looking for $\#1$ to right of pivot 31:

-4	0	2	4	21	13	11	10	31	39	37	40	59	51	49	46	60
9																

Just two elements: just sort and return $\#1$:

-4	0	2	4	21	13	11	10	31	37	39	40	59	51	49	46	60
9																

Result: 39

Selection Performance

- For this algorithm, if m roughly in middle each time, cost is

$$\begin{aligned}
 C(N) &= \begin{cases} 1, & \text{if } N = 1, \\ N + C(N/2), & \text{otherwise.} \end{cases} \\
 &= N + N/2 + \dots + 1 \\
 &= 2N - 1 \in \Theta(N)
 \end{aligned}$$

- But in worst case, get $\Theta(N^2)$, as for quicksort.
- By another, non-obvious algorithm, can get $\Theta(N)$ worst-case time for all k (take CS170).

Better than $N \lg N$?

- Can prove that if all you can do to keys is compare them then sorting must take $\Omega(N \lg N)$.
- Basic idea: there are $N!$ possible ways the input data could be scrambled.
- Therefore, your program must be prepared to do $N!$ different combinations of move operations.
- Therefore, there must be $N!$ possible combinations of outcomes of all the if tests in your program (we're assuming that comparisons are 2-way).
- Since each if test goes two ways, number of possible different outcomes for k if tests is 2^k .
- Thus, need enough tests so that $2^k > N!$, which means $k \in \Omega(\lg N!)$.
- Using Stirling's approximation,

$$m! \in \sqrt{2\pi m} \left(\frac{m}{e}\right)^m \left(1 + \Theta\left(\frac{1}{m}\right)\right),$$

this tells us that

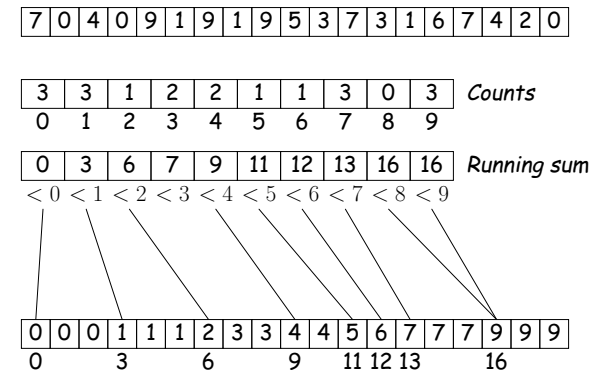
$$k \in \Omega(N \lg N).$$

Beyond Comparison: Distribution Counting

- But suppose can do more than compare keys?
- For example, how can we sort a set of N integer keys whose values range from 0 to kN , for some small constant k ?
- One technique: *count* the number of items $< 1, < 2$, etc.
- If $M_p = \#$ items with value $< p$, then in sorted order, the j^{th} item with value p must be $\#M_p + j$.
- Gives *linear-time* algorithm.

Distribution Counting Example

- Suppose all items are between 0 and 9 as in this example:



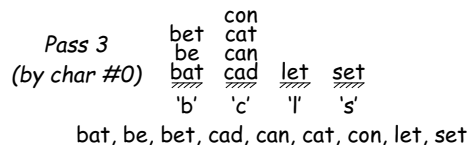
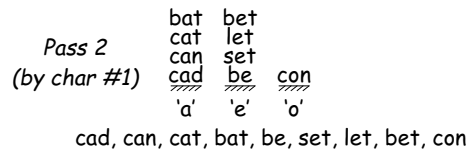
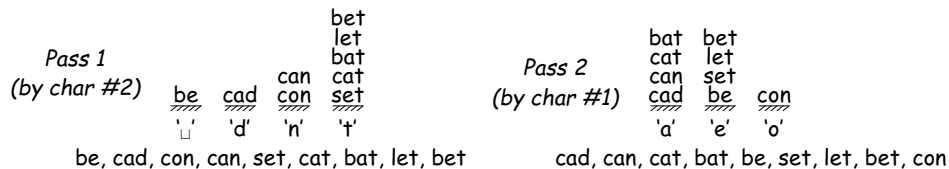
- "Counts" line gives # occurrences of each key.
- "Running sum" gives cumulative count of keys \leq each value...
- ... which tells us where to put each key:
- The first instance of key k goes into slot m , where m is the number of key instances that are $< k$.

Radix Sort

Idea: Sort keys *one character at a time*.

- Can use distribution counting for each digit.
- Can work either right to left (LSD radix sort) or left to right (MSD radix sort)
- LSD radix sort is venerable: used for punched cards.

Initial: set, cat, cad, con, bat, can, be, let, bet



MSD Radix Sort

- A bit more complicated: must keep lists from each step separate
- But, can stop processing 1-element lists

A	posn
* set, cat, cad, con, bat, can, be, let, bet	0
* bat, be, bet / cat, cad, con, can / let / set	1
bat / * be, bet / cat, cad, con, can / let / set	2
bat / be / bet / * cat, cad, con, can / let / set	1
bat / be / bet / * cat, cad, can / con / let / set	2
bat / be / bet / cad / can / cat / con / let / set	

Performance of Radix Sort

- Radix sort takes $\Theta(B)$ time where B is total size of the key data.
- Have measured other sorts as function of #records.
- How to compare?
- To have N different records, must have keys at least $\Theta(\lg N)$ long [why?]
- Furthermore, comparison actually takes time $\Theta(K)$ where K is size of key in worst case [why?]
- So $N \lg N$ comparisons really means $N(\lg N)^2$ operations.
- While radix sort takes $B = N \lg N$ time.
- On the other hand, must work to get good constant factors with radix sort.

And Don't Forget Search Trees

Idea: A search tree is in sorted order, when read in inorder.

- Need *balance* to really use for sorting [next topic].
- Given balance, same performance as heapsort: N insertions in time $\lg N$ each, plus $\Theta(N)$ to traverse, gives

$$\Theta(N + N \lg N) = \Theta(N \lg N)$$

Summary

- Insertion sort: $\Theta(Nk)$ comparisons and moves, where k is maximum amount data is displaced from final position.
 - Good for small datasets or almost ordered data sets.
- Quicksort: $\Theta(N \lg N)$ with good constant factor if data is not pathological. Worst case $O(N^2)$.
- Merge sort: $\Theta(N \lg N)$ guaranteed. Good for external sorting.
- Heapsort, treesort with guaranteed balance: $\Theta(N \lg N)$ guaranteed.
- Radix sort, distribution sort: $\Theta(B)$ (number of bytes). Also good for external sorting.