

CS61B Lectures #28

Today:

- Lower bounds on sorting by comparison
- Distribution counting, radix sorts

Readings: Today: *DS(IJ)*, Chapter 8; Next topic: Chapter 9.

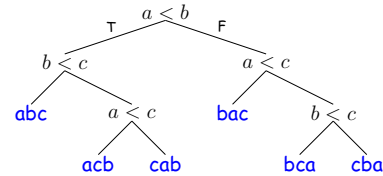
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Better than $N \lg N$?

- 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 data-moving operations.
- Therefore, there must be $N!$ possible combinations of outcomes of all the if-tests in your program, since those determine what move gets moved where (we're assuming that comparisons are 2-way).

Comparison Tree
 \propto Sorting time



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Necessary Choices

- 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 $2^k \geq N!$, which means $k \in \Omega(\lg N!)$.
- Using Stirling's approximation,

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

$$\lg(N!) \in 1/2(\lg 2\pi + \lg N) + N \lg N - N \lg e + \lg\left(1 + \Theta\left(\frac{1}{N}\right)\right)$$

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

- This tells us that k , the worst-case number of tests needed to sort N items by comparison sorting, is in $\Omega(N \lg N)$: there must be cases where we need (some multiple of) $N \lg N$ comparisons to sort N things.

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Beyond Comparison: Distribution

- 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: put the integers into N buckets, with an integer p going to bucket $\lfloor p/k \rfloor$.
- At most k keys per bucket, so concatenate and use insertion sort, which will now be fast.
- E.g., $k = 2, N = 10$:

Start:

14 3 10 13 4 2 19 17 0 9

In buckets:

| 0 | 3 2 | 4 | | 9 | 10 | 13 | 14 | 17 | 19 |

- Now insertion sort is fast. Putting in buckets takes time $\Theta(N)$, and insertion sort takes $\Theta(kN)$. When k is fixed (constant), we have sorting in time $\Theta(N)$.

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Distribution Counting

- Another technique: *count* the number of items $< 1, < 2$, etc.
- If $M_p = \# \text{items with value } < p$, then in sorted order, the j^{th} item with value p must be item $\#M_p + j$.
- Gives another *linear-time* algorithm.

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Distribution Counting Example

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

7 0 4 0 9 1 9 1 9 5 3 7 3 1 6 7 4 2 0

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
<0	<1	<2	<3	<4	<5	<6	<7	<8	<9

Running sum

0	0	0	1	1	1	2	3	3	4	4	5	6	7	7	7	9	9	9
0			3			6			9		11	12	13			16		

- "Counts" line gives # occurrences of each key.
- "Running sum" gives cumulative count of keys $<$ 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 $< k$.

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Next positions

0		3		6		9		12		15		18						

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

0	3	6	7	9	11	12	14	16	16
0	1	2	3	4	5	6	7	8	9

Next positions

												7						
0		3		6		9		12		15		18						

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

1	3	6	7	9	11	12	14	16	16
0	1	2	3	4	5	6	7	8	9

Next positions

0											7							
0		3		6		9		12		15		18						

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

1	3	6	7	10	11	12	14	16	16
0	1	2	3	4	5	6	7	8	9

Next positions

0							4				7							
0		3		6		9		12		15		18						

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	3	6	7	10	11	12	14	16	16
0	1	2	3	4	5	6	7	8	9

Next positions

0	0						4				7							
0		3		6		9		12		15		18						

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	3	6	7	10	11	12	14	16	17
0	1	2	3	4	5	6	7	8	9

Next positions

0	0						4				7				9			
0		3		6		9		12		15		18						

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	4	6	7	10	11	12	14	16	17
0	1	2	3	4	5	6	7	8	9

Next positions

0	0		1					4				7			9			
0			3					6				9			12		15	18

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	4	6	7	10	11	12	14	16	18
0	1	2	3	4	5	6	7	8	9

Next positions

0	0		1					4				7			9	9		
0			3					6				9			12		15	18

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	5	6	7	10	11	12	14	16	18
0	1	2	3	4	5	6	7	8	9

Next positions

0	0		1	1				4				7			9	9		
0			3					6				9			12		15	18

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	5	6	7	10	11	12	14	16	19
0	1	2	3	4	5	6	7	8	9

Next positions

0	0		1	1				4				7			9	9	9	
0			3					6				9			12		15	18

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	5	6	7	10	12	12	14	16	19
0	1	2	3	4	5	6	7	8	9

Next positions

0	0		1	1				4		5		7			9	9	9
0			3					6		9		12			15		18

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	5	6	8	10	12	12	14	16	19
0	1	2	3	4	5	6	7	8	9

Next positions

0	0		1	1			3		4		5		7			9	9	9
0			3				6		9		12		15			18		

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	5	6	8	10	12	12	15	16	19
0	1	2	3	4	5	6	7	8	9

Next positions

0	0		1	1		3		4		5		7	7		9	9	9
0			3		6			9		12		15		18			

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	5	6	9	10	12	12	15	16	19
0	1	2	3	4	5	6	7	8	9

Next positions

0	0		1	1		3	3	4		5		7	7		9	9	9
0			3		6			9		12		15		18			

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	6	6	9	10	12	12	15	16	19
0	1	2	3	4	5	6	7	8	9

Next positions

0	0		1	1	1		3	3	4		5		7	7		9	9	9
0			3		6			9		12		15		18				

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	6	6	9	10	12	13	15	16	19
0	1	2	3	4	5	6	7	8	9

Next positions

0	0		1	1	1		3	3	4		5	6	7	7		9	9	9
0			3		6			9		12		15		18				

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	6	6	9	10	12	13	16	16	19
0	1	2	3	4	5	6	7	8	9

Next positions

0	0		1	1	1		3	3	4		5	6	7	7	7	9	9	9
0			3		6			9		12		15		18				

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	6	6	9	11	12	13	16	16	19
0	1	2	3	4	5	6	7	8	9

Next positions

0	0		1	1	1		3	3	4	4	5	6	7	7	7	9	9	9
0			3		6			9		12		15		18				

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

2	6	7	9	11	12	13	16	16	19
0	1	2	3	4	5	6	7	8	9

Next positions

0	0		1	1	1	2	3	3	4	4	5	6	7	7	7	9	9	9
0			3		6		9		12		15		18					

Output

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Distribution Counting Example (II)

7	0	4	0	9	1	9	1	9	5	3	7	3	1	6	7	4	2	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

3	3	1	2	2	1	1	3	0	3
0	1	2	3	4	5	6	7	8	9

Counts

0	3	6	7	9	11	12	13	16	16
0	1	2	3	4	5	6	7	8	9

Running sum of Counts

3	6	7	9	11	12	13	16	16	19
0	1	2	3	4	5	6	7	8	9

Next positions

0	0	0	1	1	1	2	3	3	4	4	5	6	7	7	7	9	9	9
0			3		6		9		12		15		18					

Output

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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

Pass 1 (by char #2)

bet	cat	can	con	set
bat	cat	can	con	set
bet	cat	can	con	set
bat	cat	can	con	set
bet	cat	can	con	set
bat	cat	can	con	set
bet	cat	can	con	set
bat	cat	can	con	set

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

Pass 2 (by char #1)

bat	bet	cat	let	set
bat	bet	cat	let	set
bat	bet	cat	let	set
bat	bet	cat	let	set
bat	bet	cat	let	set
bat	bet	cat	let	set
bat	bet	cat	let	set
bat	bet	cat	let	set

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

Pass 3 (by char #0)

bet	cat	can	con	set
bet	cat	can	con	set
bet	cat	can	con	set
bet	cat	can	con	set
bet	cat	can	con	set
bet	cat	can	con	set
bet	cat	can	con	set
bet	cat	can	con	set

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

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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, con / con / let / set	2
bat / be / bet / cad / can / cat / con / let / set	

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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 would take $B = N \lg N$ time with minimal-length keys.
- On the other hand, must work to get good constant factors with radix sort.

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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

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

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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.