CS4102 Algorithms
Spring 2019

Warm up

Show $\log(n!) = \Theta(n \log n)$

Hint: show $n! \le n^n$

Hint 2: show $n! \ge \left(\frac{n}{2}\right)^{\frac{n}{2}}$

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

$$n! = n \cdot (n-1) \cdot (n-2) \cdot \ldots \cdot 2 \cdot 1$$

$$= \quad < \quad < \quad < \quad <$$

$$n^n = n \cdot \quad n \quad \cdot \quad n \quad \cdot \ldots \cdot n \cdot n$$

$n! \le n^n$

$\Rightarrow \log(n!) \le \log(n^n)$

$\Rightarrow \log(n!) \le n \log n$

$\Rightarrow \log(n!) = O(n \log n)$

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$\log n! = \Omega(n \log n)$

$$n! = n \cdot (n-1) \cdot (n-2) \cdot \ldots \cdot \frac{n}{2} \cdot \left(\frac{n}{2} - 1\right) \cdot \ldots \cdot 2 \cdot 1$$

$$> \quad > \quad > \quad = \quad > \quad > \quad =$$

$$\left(\frac{n}{2}\right)^{\frac{n}{2}} = \frac{n}{2} \cdot \frac{n}{2} \cdot \frac{n}{2} \cdot \ldots \cdot \frac{n}{2} \cdot 1 \cdot \ldots \cdot 1 \cdot 1$$

$n! \ge \left(\frac{n}{2}\right)^{\frac{n}{2}}$

$\Rightarrow \log(n!) \ge \log\left(\left(\frac{n}{2}\right)^{\frac{n}{2}}\right)$

$\Rightarrow \log(n!) \ge \frac{n}{2} \log \frac{n}{2}$

$\Rightarrow \log(n!) = \Omega(n \log n)$

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Today's Keywords

- Divide and Conquer
- Sorting
- Quicksort
- Decision Tree
- Worst case lower bound

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CLRS Readings

- Chapter 7
- Chapter 8

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Homeworks

- HW2 due 11pm tonight!
  – Divide and conquer
  – Closest Pair of Points
  – Remember to submit relevant .java or .py files (no .zip!)
- HW3 due 11pm Wednesday Feb. 20
  – Divide and conquer
  – Written (use LaTeX!)

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Quicksort

- Idea: pick a pivot element, recursively sort two sublists around that element
- Divide: select an element p, Partition(p)
- Conquer: recursively sort left and right sublists
- Combine: Nothing!

Partition (Divide step)

- Given: a list, a pivot value p

Start: unordered list

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

Goal: All elements $<p$ on left, all $>p$ on right

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

Is it worth it?

- Using Quickselect to pick median guarantees $\Theta(n \log n)$ run time
  - Approach has very large constants
  - If you really want $\Theta(n \log n)$, better off using MergeSort
- Better approach: Random pivot
  - Very small constant (very fast algorithm)
  - Expected to run in $\Theta(n \log n)$ time
    - Why? Unbalanced partitions are very unlikely

Quicksort Run Time

- If the partition is always $\frac{n}{10}$ th order statistic:

$$T(n) = T\left(\frac{n}{10}\right) + T\left(\frac{9n}{10}\right) + n$$

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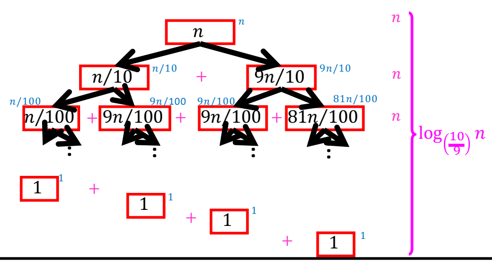
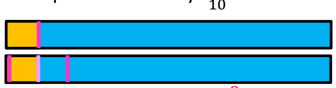
$$T(n) = T\left(\frac{n}{10}\right) + T\left(\frac{9n}{10}\right) + n \;\; = T\left(\frac{n}{10/9}\right)$$



Quicksort Run Time

- If the partition is always $\frac{n}{10}$ th order statistic:



$$T(n) = T\left(\frac{n}{10}\right) + T\left(\frac{9n}{10}\right) + n$$

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

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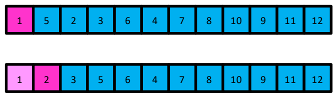
Quicksort Run Time

- If the partition is always d^{th} order statistic:



- Then we shorten by d each time

$$T(n) = T(n-d) + n$$

$$T(n) = O(n^2)$$

What's the probability of this occurring?

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Probability of n^2 run time

We must consistently select pivot from within the first d terms

Probability first pivot is among d smallest: $\frac{d}{n}$

Probability second pivot is among d smallest: $\frac{d}{n-d}$

Probability all pivot are among d smallest:

$$\frac{d}{n} \cdot \frac{d}{n-d} \cdot \frac{d}{n-2d} \cdot \ldots \cdot \frac{d}{2d} \cdot 1 = \frac{1}{\left(\frac{n}{d}\right)!}$$

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Random Pivot

- Using Quickselect to pick median guarantees $\Theta(n \log n)$ run time
  – Approach has very large constants
  – If you really want $\Theta(n \log n)$, better off using MergeSort
- Better approach: Random pivot
  – Very small constant (very fast algorithm)
  – Expected to run in $\Theta(n \log n)$ time
    - Why? Unbalanced partitions are very unlikely

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Formal Argument for $n \log n$ Average

- Remember, run time counts comparisons!
- Quicksort only compares against the pivot
  - Element i only compared to element j if one of them was the pivot

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Partition (Divide step)

- Given: a list, a pivot value p

Start: unordered list

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

Goal: All elements $< p$ on left, all $> p$ on right

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

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Formal Argument for $n \log n$ Average

- What is the probability of comparing two given elements?

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

- (Probability of comparing 3 and 4) = 1
  - Why?
    - Otherwise I wouldn't know which came first
    - ANY sorting algorithm must compare adjacent elements

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Formal Argument for $n \log n$ Average

- What is the probability of comparing two given elements?

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

- (Probability of comparing 1 and 12) = $\frac{2}{12}$
  - Why?
    - We only compare 1 with 12 if either was chosen as the first pivot
    - Otherwise they would be divided into opposite sublists

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Formal Argument for $n \log n$ Average

- Probability of comparing i and j (where $j > i$):
  - inversely proportional to the number of elements between i and j
    - $\frac{2}{j-i+1}$
- Expected (average) number of comparisons:
    - $\sum_{i<j} \frac{2}{j-i+1}$

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Expected number of Comparisons

Consider when $i = 1$

$$\sum_{i<j} \frac{2}{j-i+1}$$

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

Compared if 1 or 2 are chosen as pivot
(these will always be compared)

Sum so far: $\frac{2}{2}$

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Expected number of Comparisons

Consider when $i = 1$ $\sum_{i<j} \frac{2}{j-i+1}$

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

Compared if 1 or 3 are chosen as pivot
(but not if 2 is ever chosen)

Sum so far: $\frac{2}{2} + \frac{2}{3}$

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Expected number of Comparisons

Consider when $i = 1$ $\sum_{i<j} \frac{2}{j-i+1}$

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

Compared if 1 or 4 are chosen as pivot
(but not if 2 or 3 are chosen)

Sum so far: $\frac{2}{2} + \frac{2}{3} + \frac{2}{4}$

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Expected number of Comparisons

Consider when $i = 1$ $\sum_{i<j} \frac{2}{j-i+1}$

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

Compared if 1 or 12 are chosen as pivot
(but not if 2 -> 11 are chosen)

Overall sum: $\frac{2}{2} + \frac{2}{3} + \frac{2}{4} + \frac{2}{5} + \cdots + \frac{2}{n}$

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Expected number of Comparisons

$$\sum_{i<j} \frac{2}{j-i+1}$$

When $i = 1$: $2\left(\frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \cdots + \frac{1}{n}\right)$

n terms overall

$$\sum_{i<j} \frac{2}{j-i+1} \leq 2n\left(\frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{n}\right) \quad \Theta(\log n)$$

Quicksort overall: expected $\Theta(n \log n)$

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Sorting, so far

- Sorting algorithms we have discussed:
  - Mergesort $O(n \log n)$
  - Quicksort $O(n \log n)$
- Other sorting algorithms (will discuss):
  - Bubblesort $O(n^2)$
  - Insertionsort $O(n^2)$
  - Heapsort $O(n \log n)$

Can we do better than $O(n \log n)$?

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Worst Case Lower Bounds

- Prove that there is no algorithm which can sort faster than $O(n \log n)$
- Non-existence proof!
  - Very hard to do

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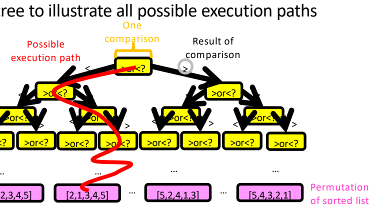
Strategy: Decision Tree

- Sorting algorithms use comparisons to figure out the order of input elements
- Draw tree to illustrate all possible execution paths



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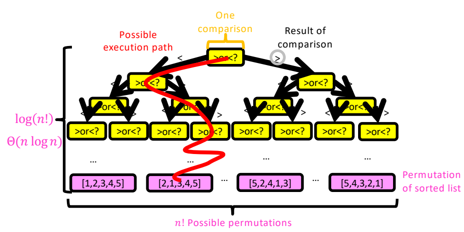
Strategy: Decision Tree

- Worst case run time is the longest execution path
- i.e., "height" of the decision tree



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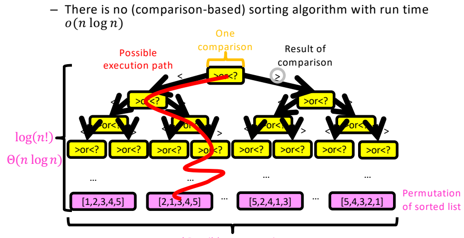
Strategy: Decision Tree

- Conclusion: Worst Case Optimal run time of sorting is $\Theta(n \log n)$
  - There is no (comparison-based) sorting algorithm with run time $o(n \log n)$



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Sorting, so far

- Sorting algorithms we have discussed:
  - Mergesort $O(n \log n)$ Optimal!
  - Quicksort $O(n \log n)$ Optimal!
- Other sorting algorithms
  - Bubblesort $O(n^2)$
  - Insertionsort $O(n^2)$
  - Heapsort $O(n \log n)$ Optimal!

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Speed Isn't Everything

- Important properties of sorting algorithms:
- Run Time
  - Asymptotic Complexity
  - Constants
- In Place (or In-Situ)
  - Done with only constant additional space
- Adaptive
  - Faster if list is nearly sorted
- Stable
  - Equal elements remain in original order
- Parallelizable
  - Runs faster with many computers

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