CSE 421

Integer Multiplication, Median

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Median
Finding Median

Choose a number $w$ from $x_1, \ldots, x_n$

Define

- $S_<(w) = \{x_i : x_i < w\}$
- $S_=(w) = \{x_i : x_i = w\}$
- $S_>(w) = \{x_i : x_i > w\}$

Can be computed in linear time

Solve the problem recursively

- If $k \leq |S_<(w)|$, output $Sel(S_<(w), k)$
- Else if $k \leq |S_<(w)| + |S_=(w)|$, output $w$
- Else output $Sel(S_>(w), k - |S_<(w)| - |S_=(w)|)$
How to lower bound $|S_{<}(w)|, |S_{>}(w)|$?

- $|S_{<}(w)| \geq 2 \left( \frac{n}{6} \right) = \frac{n}{3}$
- $|S_{>}(w)| \geq 2 \left( \frac{n}{6} \right) = \frac{n}{3}$.

$\frac{n}{3} \leq |S_{<}(w)|, |S_{>}(w)| \leq \frac{2n}{3}$

So, what is the running time?
Asymptotic Running Time?

- If $k \leq |S_<(w)|$, output $Sel(S_<(w), k)$
- Else if $k \leq |S_<(w)| + |S_=(w)|$, output $w$
- Else output $Sel(S_>(w), k - S_<(w) - S_=(w))$

Where $\frac{n}{3} \leq |S_<(w)|, |S_>(w)| \leq \frac{2n}{3}$

$$T(n) = T\left(\frac{n}{3}\right) + T\left(\frac{2n}{3}\right) + O(n) \Rightarrow T(n) = O(n \log n)$$
An Improved Idea

Partition into \( \frac{n}{5} \) sets. Sort each set and set \( w = \text{Sel}(\text{midpoints}, \frac{n}{10}) \)

- \( |S_<(w)| \geq 3 \left( \frac{n}{10} \right) = \frac{3n}{10} \)
- \( |S_>(w)| \geq 3 \left( \frac{n}{10} \right) = \frac{3n}{10} \)

\[
T(n) = T\left( \frac{n}{5} \right) + T\left( \frac{7n}{10} \right) + O(n) \Rightarrow T(n) = O(n)
\]
An Improved Idea

Sel(S, k) {
    n ← |S|
    If (n < ??) return ??
    Partition S into n/5 sets of size 5
    Sort each set of size 5 and let M be the set of medians, so |M| = n/5
    Let w = Sel(M, n/10)
    For i = 1 to n{
        If $x_i < w$ add x to $S_<(w)$
        If $x_i > w$ add x to $S_(w)$
        If $x_i = w$ add x to $S_=(w)$
    }
    If (k ≤ |$S_<(w)$|)
        return Sel($S_<(w)$, k)
    else if (k ≤ |$S_<(w)$| + |$S_=(w)$|)
        return w;
    else
        return Sel($S_(w)$, k − |$S_<(w)$| − |$S_=(w)$|)
}
D&C Summary

Idea:

“Two halves are better than a whole”
  • if the base algorithm has super-linear complexity.

“If a little's good, then more's better”
  • repeat above, recursively

• Applications: Many.
  • Binary Search, Merge Sort, (Quicksort),
  • Root of a Function
  • Closest points,
  • Integer multiplication
  • Median
  • Matrix Multiplication
Approximation Algorithms
Many of the important problems in real world are NP-complete.

SAT, Set Cover, Graph Coloring, TSP, Max IND Set, Vertex Cover, …

So, we cannot find optimum solutions in polynomial time. What to do instead?

• Find optimum solution of special cases (e.g., random inputs)

• Find near optimum solution in the worst case
Approximation Algorithm

Polynomial-time Algorithms with a guaranteed approximation ratio.

\[ \alpha = \frac{\text{Cost of computed solution}}{\text{Cost of the optimum}} \]

\text{worst case} over all instances.

\textbf{Goal}: For each NP-hard problem find an approximation algorithm with the best possible approximation ratio.
Given a graph $G=(V,E)$, find smallest set of vertices touching every edge
Greedy algorithms are typically used in practice to find a (good) solution to NP-hard problems

**Strategy (1):** Iteratively, include a vertex that covers most new edges

Q: Does this give an optimum solution?
A: No,
Greedy (1): Pick vertex that covers the most
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Greedy Vertex cover = 20

OPT Vertex cover = 8
Greedy (1): Pick vertex that covers the most
n vertices. Each vertex has one edge into each $B_i$

$B_n$ $B_{n-1}$ $\cdots$ $B_i$ $B_1$

$|B_i| = n/i$

Each vertex in $B_i$ has $i$ edges to top

Greedy pick bottom vertices $= n + \frac{n}{2} + \frac{n}{3} + \cdots + 1 \approx n \ln n$

OPT pick top vertices $= n$
A Different Greedy Rule

Greedy 2: Iteratively, pick both endpoints of an uncovered edge.

Vertex cover = 6
Greedy 2: Pick Both endpoints of an uncovered edge

Greedy vertex cover = 16

OPT vertex cover = 8
**Thm:** Size of greedy (2) vertex cover is at most twice as big as size of optimal cover

**Pf:** Suppose Greedy (2) picks endpoints of edges $e_1, \ldots, e_k$. Since these edges do not touch, every valid cover must pick one vertex from each of these edges!

i.e., $OPT \geq k$.

But the size of greedy cover is $2k$. So, Greedy is a 2-approximation.
Set Cover

Given a number of sets on a ground set of elements,

**Goal**: choose minimum number of sets that cover all.

e.g., a company wants to hire employees with certain skills.
Set Cover

Given a number of sets on a ground set of elements,

Goal: choose minimum number of sets that cover all.

Set cover = 4
A Greedy Algorithm

Strategy: Pick the set that maximizes # new elements covered
A Greedy Algorithm

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A Greedy Algorithm

**Strategy**: Pick the set that maximizes # new elements covered
A Greedy Algorithm

**Strategy:** Pick the set that maximizes # new elements covered

**Thm:** Greedy has $\ln n$ approximation ratio
A Tight Example for Greedy
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Greedy = 5

OPT = 2
Thm: If the best solution has k sets, greedy finds at most k ln(n) sets.

Pf: Suppose OPT=k
There is set that covers 1/k fraction of remaining elements, since there are k sets that cover all remaining elements.
So in each step, algorithm will cover 1/k fraction of remaining elements.

#elements uncovered after t steps

\[ \leq n \left( 1 - \frac{1}{k} \right)^t \leq ne^{-\frac{t}{k}} \]

So after \( t = k \ln n \) steps, # uncovered elements < 1.