Chapter 14

Randomized Algorithms: QuickSort and QuickSelect

CS 473: Fundamental Algorithms, Fall 2011
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14.1 Slick analysis of QuickSort

14.1.0.1 A Slick Analysis of QuickSort

Let $Q(A)$ be number of comparisons done on input array A:

(A) For $1 \leq i < j < n$ let R_{ij} be the event that rank i element is compared with rank j element.

(B) X_{ij} is the indicator random variable for R_{ij}. That is, $X_{ij} = 1$ if rank i is compared with rank j element, otherwise 0.

$$Q(A) = \sum_{1 \leq i < j \leq n} X_{ij}$$

and hence by linearity of expectation,

$$\mathbf{E}\Big[Q(A)\Big] = \sum_{1 \leq i < j \leq n} \mathbf{E}[X_{ij}] = \sum_{1 \leq i < j \leq n} \mathbf{Pr}[R_{ij}].$$

14.1.0.2 A Slick Analysis of QuickSort

Question: What is $\mathbf{Pr}[R_{ij}]$?

7	5	9	1	3	4	8	6

With ranks:

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

As such, probability of comparing 5 to 8 is $\mathbf{Pr}[R_{4,7}]$.

(A) If pivot too small (say 3 [rank 2]). Partition and call recursively:

$\boxed{7 \mid 5 \mid 9 \mid 1 \mid 3 \mid 4 \mid 8 \mid 6} \Longrightarrow \boxed{1 \quad 3 \quad 7 \mid 5 \mid 9 \mid 4 \mid 8 \mid 6}$

Decision if to compare 5 to 8 is moved to subproblem.

(B) If pivot too large (say 9 [rank 8]):

| 7 | 5 | 9 | 1 | 3 | 4 | 8 | 6 | $\Longrightarrow$ | 7 | 5 | 1 | 3 | 4 | 8 | 6 | 9 |

Decision if to compare 5 to 8 moved to subproblem.

14.1.1 A Slick Analysis of QuickSort

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

As such, probability of comparing 5 to 8 is $\mathbf{Pr}[R_{4,7}]$.

14.1.1.1 Question: What is $\mathbf{Pr}[R_{i,j}]$?

(A) If pivot is 5 (rank 4). Bingo!

| 7 | 5 | 9 | 1 | 3 | 4 | 8 | 6 | $\Longrightarrow$ | 1 | 3 | 4 | 5 | 7 | 9 | 8 | 6 |

(B) If pivot is 8 (rank 7). Bingo!

| 7 | 5 | 9 | 1 | 3 | 4 | 8 | 6 | $\Longrightarrow$ | 7 | 5 | 1 | 3 | 4 | 6 | 8 | 9 |

(C) If pivot in between the two numbers (say 6 [rank 5]):

| 7 | 5 | 9 | 1 | 3 | 4 | 8 | 6 | $\Longrightarrow$ | 5 | 1 | 3 | 4 | 6 | 7 | 8 | 9 |

5 and 8 will never be compared to each other.

14.1.2 A Slick Analysis of QuickSort

14.1.2.1 Question: What is $\mathbf{Pr}[R_{i,j}]$?

Conclusion:

$R_{i,j}$ happens if and only if:

ith or jth ranked element is the first pivot out of ith to jth ranked elements

How to analyze this?

Thinking acrobatics!

(A) Assign every element in the array a random priority (say in $[0, 1]$).
(B) Choose pivot to be the element with lowest priority in subproblem.
(C) Equivalent to picking pivot uniformly at random (as **QuickSort** do).

14.1.3 A Slick Analysis of QuickSort

14.1.3.1 Question: What is $\mathbf{Pr}[R_{i,j}]$?

How to analyze this?

Thinking acrobatics!

(A) Assign every element in the array a random priority (say in $[0, 1]$).
(B) Choose pivot to be the element with lowest priority in subproblem.

$\implies$ $R_{i,j}$ happens if either i or j have lowest priority out of elements rank i to j,

As such

$$\mathbf{Pr}[R_{i,j}] = \frac{2}{j - i + 1}.$$

14.1.3.2 A Slick Analysis of QuickSort

Question: What is $\mathbf{Pr}[R_{ij}]$?

Lemma 14.1.1 $\mathbf{Pr}[R_{ij}] = \frac{2}{(j-i+1)}$.

Proof: Let $a_1, \ldots, a_i, \ldots, a_j, \ldots, a_n$ be elements of A in sorted order. Let $S = \{a_i, a_{i+1}, \ldots, a_j\}$

Observation: If pivot is chosen outside S then all of S either in left array or right array.

Observation: a_i and a_j separated when a pivot is chosen from S for the first time. Once separated no comparison.

Observation: a_i is compared with a_j if and only if either a_i or a_j is chosen as a pivot from S at separation... ∎

14.1.4 A Slick Analysis of QuickSort

14.1.4.1 Continued...

Lemma 14.1.2 $\mathbf{Pr}[R_{ij}] = \frac{2}{(j-i+1)}$.

Proof: Let $a_1, \ldots, a_i, \ldots, a_j, \ldots, a_n$ be sort of A. Let $S = \{a_i, a_{i+1}, \ldots, a_j\}$

Observation: a_i is compared with a_j if and only if either a_i or a_j is chosen as a pivot from S at separation.

Observation: Given that pivot is chosen from S the probability that it is a_i or a_j is exactly $2/|S| = 2/(j-i+1)$ since the pivot is chosen uniformly at random from the array. ∎

14.1.5 A Slick Analysis of QuickSort

14.1.5.1 Continued...

$$\mathbf{E}\Big[Q(A)\Big] = \sum_{1 \le i < j \le n} \mathbf{E}[X_{ij}] = \sum_{1 \le i < j \le n} \mathbf{Pr}[R_{ij}].$$

Lemma 14.1.3 $\mathbf{Pr}[R_{ij}] = \frac{2}{(j-i+1)}$.

$$
\begin{aligned}
\mathbf{E}\Big[Q(A)\Big] &= \sum_{1\le i<j\le n} \mathbf{Pr}[R_{ij}] = \sum_{1\le i<j\le n} \frac{2}{j-i+1} \\
&= \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \frac{2}{j-i+1} = 2\sum_{i=1}^{n-1}\sum_{i<j}^{n} \frac{1}{j-i+1} \\
&= 2\sum_{i=1}^{n-1}(H_{n-i+1}-1) \le 2\sum_{1\le i<n} H_n \\
&\le 2nH_n = O(n\log n)
\end{aligned}
$$

14.2 QuickSelect with high probability

14.2.1 Yet another analysis of QuickSort

14.2.1.1 You should never trust a man who has only one way to spell a word

Consider element e in the array.

Consider the subproblems it participates in during **QuickSort** execution:
$S_1, S_2, \ldots, S_k$.

Definition

e is lucky in the jth iteration if $|S_j| \le (3/4)\,|S_{j-1}|$.

Key observation

The event e is lucky in jth iteration
is independent of
the event that e is lucky in kth iteration,
(If $j \ne k$)
$X_j = 1$ **iff** e is lucky in the jth iteration.

14.2.2 Yet another analysis of QuickSort

14.2.2.1 Continued...

Observation

$\mathbf{Pr}[X_j = 1] = 1/2$.

Observation

If $X_1 + X_2 + \ldots X_k = \lceil \log_{4/3} n \rceil$ then e subproblem is of size one. Done!

14.2.3 Yet another analysis of QuickSort

14.2.3.1 Continued...

Observation

Probability e participates in $\geq k = 40\lceil \log_{4/3} n \rceil$ subproblems. Is equal to

$$
\begin{aligned}
&\mathbf{Pr}\Big[X_1 + X_2 + \ldots + X_k \leq \lceil \log_{4/3} n \rceil\Big] \\
&\leq \mathbf{Pr}[X_1 + X_2 + \ldots + X_k \leq k/4] \\
&\leq 2 \cdot 0.68^{k/4} \leq 1/n^5.
\end{aligned}
$$

Conclusion

QuickSort takes $O(n \log n)$ time with high probability.

14.3 Randomized Selection

14.3.0.2 Randomized Quick Selection

Input Unsorted array A of n integers

Goal Find the jth smallest number in A (*rank* j number)

Randomized Quick Selection

(A) Pick a pivot element *uniformly at random* from the array
(B) Split array into 3 subarrays: those smaller than pivot, those larger than pivot, and the pivot itself.
(C) Return pivot if rank of pivot is j
(D) Otherwise recurse on one of the arrays depending on j and their sizes.

14.3.0.3 Algorithm for Randomized Selection

Assume for simplicity that A has distinct elements.

```
QuickSelect(A, j):
    Pick pivot x uniformly at random from
    Partition A into A_less, x, and A_greater
    if (|A_less| = j - 1) then
        return x
    if (|A_less| >= j) then
        return QuickSelect(A_less, j)
    else
        return QuickSelect(A_greater, j - |A
```

14.3.0.4 QuickSelect analysis

(A) $S_1, S_2, \ldots, S_k$ be the subproblems considered by the algorithm.
Here $|S_1| = n$.
(B) S_i would be ***successful*** if $|S_i| \leq (3/4)\,|S_{i-1}|$
(C) Y_1 = number of recursive calls till first successful iteration.
Clearly, total work till this happens is $O(Y_1 n)$.
(D) n_i = size of the subproblem immediately after the $(i-1)$th successful iteration.
(E) Y_i = number of recursive calls after the $(i-1)$th successful call, till the ith successful iteration.
(F) Running time is $O(\sum_i n_i Y_i)$.

14.3.0.5 QuickSelect analysis

Example

S_i = subarray used in ith recursive call
$|S_i|$ = size of this subarray
Red indicates successful iteration.

Inst'	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9
$\lvert S_i\rvert$	100	70	60	50	40	30	25	5	2
Succ'	$Y_1 = 2$		$Y_2 = 4$				$Y_3 = 2$		$Y_4 = 1$
$n_i =$	$n_1 = 100$		$n_2 = 60$				$n_3 = 25$		$n_4 = 2$

(A) All the subproblems after $(i-1)$th successful iteration till ith successful iteration have size $\leq n_i$.
(B) Total work: $O(\sum_i n_i Y_i)$.

14.3.0.6 QuickSelect analysis

Total work: $O(\sum_i n_i Y_i)$.
We have:
(A) $n_i \leq (3/4) n_{i-1} \leq (3/4)^{i-1} n$.
(B) Y_i is a random variable with geometric distribution
Probability of $Y_i = k$ is $1/2^i$.
(C) $\mathbf{E}[Y_i] = 2$.
As such, expected work is proportional to

$$\mathbf{E}\left[\sum_i n_i Y_i\right] = \sum_i \mathbf{E}[n_i Y_i] \leq \sum_i \mathbf{E}\left[(3/4)^{i-1} n Y_i\right]$$
$$= n \sum_i (3/4)^{i-1}\, \mathbf{E}[Y_i] = n \sum_{i=1} (3/4)^{i-1} 2 \leq 8n.$$

14.3.0.7 QuickSelect analysis

Theorem 14.3.1 *The expected running time of* **QuickSelect** *is* $O(n)$.

14.3.1 QuickSelect analysis

14.3.1.1 Analysis via Recurrence

(A) Given array A of size n let $Q(A)$ be number of comparisons of randomized selection on A for selecting rank j element.
(B) Note that $Q(A)$ is a random variable
(C) Let A^i_{less} and A^i_{greater} be the left and right arrays obtained if pivot is rank i element of A.
(D) Algorithm recurses on A^i_{less} if $j < i$ and recurses on A^i_{greater} if $j > i$ and terminates if $j = i$.

$$\begin{aligned} Q(A) &= n + \sum_{i=1}^{j-1} \mathbf{Pr}[\text{pivot has rank } i]\, Q(A^i_{\text{greater}}) \\ &\quad + \sum_{i=j+1}^{n} \mathbf{Pr}[\text{pivot has rank } i]\, Q(A^i_{\text{less}}) \end{aligned}$$

14.3.1.2 Analyzing the Recurrence

As in **QuickSort** we obtain the following recurrence where $T(n)$ is the worst-case expected time.

$$T(n) \le n + \frac{1}{n}\left(\sum_{i=1}^{j-1} T(n-i) + \sum_{i=j}^{n} T(i-1)\right).$$

Theorem 14.3.2 $T(n) = O(n)$.

Proof: (Guess and) Verify by induction (see next slide). ∎

14.3.1.3 Analyzing the recurrence

Theorem 14.3.3 $T(n) = O(n)$.

Prove by induction that $T(n) \le \alpha n$ for some constant $\alpha \ge 1$ to be fixed later.
Base case: $n = 1$, we have $T(1) = 0$ since no comparisons needed and hence $T(1) \le \alpha$.
Induction step: Assume $T(k) \le \alpha k$ for $1 \le k < n$ and prove it for $T(n)$. We have by the recurrence:

$$\begin{aligned} T(n) &\le n + \frac{1}{n}\left(\sum_{i=1}^{j-1} T(n-i) + \sum_{i=j^n} T(i-1)\right) \\ &\le n + \frac{\alpha}{n}\left(\sum_{i=1}^{j-1} (n-i) + \sum_{i=j}^{n} (i-1)\right) \quad \text{by applying induction} \end{aligned}$$

14.3.1.4 Analyzing the recurrence

$$
\begin{aligned}
T(n) &\leq n + \frac{\alpha}{n}(\sum_{i=1}^{j-1}(n-i) + \sum_{i=j}^{n}(i-1)) \\
&\leq n + \frac{\alpha}{n}((j-1)(2n-j)/2 + (n-j+1)(n+j-2)/2) \\
&\leq n + \frac{\alpha}{2n}(n^2 + 2nj - 2j^2 - 3n + 4j - 2) \\
&\quad \text{above expression maximized when } j = (n+1)/2\text{: calculus} \\
&\leq n + \frac{\alpha}{2n}(3n^2/2 - n) \quad \text{substituting } (n+1)/2 \text{ for } j \\
&\leq n + 3\alpha n/4 \\
&\leq \alpha n \quad \text{for any constant } \alpha \geq 4
\end{aligned}
$$

14.3.1.5 Comments on analyzing the recurrence

(A) Algebra looks messy but intuition suggest that the median is the hardest case and hence can plug $j = n/2$ to simplify without calculus

(B) Analyzing recurrences comes with practice and after a while one can see things more intuitively

John Von Neumann:

Young man, in mathematics you don't understand things. You just get used to them.

14.3.1.6 If there is time...

Sketch Treaps and how **QuickSort** implies $O(\log n)$ time per operation (with high probability).