Chapter 10

Randomized Algorithms II – High Probability

CS 573: Algorithms, Fall 2014
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10.1 Movie...

10.2 Understanding the binomial distribution

10.2.0.1 Binomial distribution

\( X_n = \) numbers of heads when flipping a coin \( n \) times.

Claim

\[ \Pr[X_n = i] = \binom{n}{i} \left(\frac{1}{2}\right)^i. \]

Where: \( \binom{n}{k} = \frac{n!}{(n-k)!k!} \).

Indeed, \( \binom{n}{i} \) is the number of ways to choose \( i \) elements out of \( n \) elements (i.e., pick which \( i \) coin flip come up heads).

Each specific such possibility (say 0100010...) had probability \( 1/2^n \).

10.2.0.2 Massive randomness.. Is not that random.

Consider flipping a fair coin \( n \) times independently, head given 1, tail gives zero. How many heads? ...we get a binomial distribution.
$n = 1024$

$0 \leq n \leq 1000$

$0 \leq \text{probability} \leq 0.025$

$0 \leq n \leq 4096$

$0 \leq \text{probability} \leq 0.014$
10.2.0.3 Massive randomness.. Is not that random.

This is known as concentration of mass.
This is a very special case of the law of large numbers.

10.2.1 Side note...

10.2.1.1 Law of large numbers (weakest form)...

Informal statement of law of large numbers

For \( n \) large enough, the middle portion of the binomial distribution looks like (converges to) the normal/Gaussian distribution.

10.2.1.2 Massive randomness.. Is not that random.

Intuitive conclusion

Randomized algorithm are unpredictable in the tactical level, but very predictable in the strategic level.
10.2.1.3 What is really hiding below the Normal distribution?

10.3 QuickSort with high probability

10.4 AlgorithmQuickSort and Treaps with High Probability

10.4.0.4 Show that QuickSort running time is $O(n \log n)$

(A) **QuickSort** picks a pivot, splits into two subproblems, and continues recursively.

(B) Track single element in input.

(C) Game ends, when this element is alone in subproblem.

(D) Show every element in input, participates $\leq 32 \ln n$ rounds (with high enough probability).

(E) $E_i$: event $i$th element participates $\geq 32 \ln n$ rounds.

(F) $C_{QS}$: number of comparisons performed by QuickSort.

(G) Running time $O(C_{QS})$.

(H) Probability of failure is $\alpha = \Pr[C_{QS} \geq 32 n \ln n] \leq \Pr[\bigcup_i E_i] \leq \sum_{i=1}^n \Pr[E_i]$.

\[ \leq \sum_{i=1}^n \frac{1}{n^3} = \frac{1}{n^2}. \]

... by the union bound.

10.4.0.5 Show that QuickSort running time is $O(n \log n)$

(A) Probability of failure is $\alpha = \Pr[C_{QS} \geq 32 n \ln n] \leq \Pr[\bigcup_i E_i] \leq \sum_{i=1}^n \Pr[E_i]$.

(B) **Union bound**: for any two events $A$ and $B$: $\Pr[A \cup B] \leq \Pr[A] + \Pr[B]$.

(C) Assume: $\Pr[E_i] \leq 1/n^3$.

(D) Bad probability... $\alpha \leq \sum_{i=1}^n \Pr[E_i] \leq \sum_{i=1}^n \frac{1}{n^3} = \frac{1}{n^2}$.

(E) $\implies$ **QuickSort** performs $\leq 32 n \ln n$ comparisons, w.h.p.

(F) $\implies$ **QuickSort** runs in $O(n \log n)$ time, with high probability.
10.4.1 Proving that an element participates in small number of rounds

10.4.2 Proving that an element...

10.4.2.1 ... participates in small number of rounds.

(A) $n$: number of elements in input for QuickSort.
(B) $x$: Arbitrary element $x$ in input.
(C) $S_1$: Input.
(D) $S_i$: input to $i$th level recursive call that include $x$.
(E) $x$ lucky in $j$th iteration, if balanced split...

$|S_{j+1}| \leq (3/4) |S_j|$ and $|S_j \setminus S_{j+1}| \leq (3/4) |S_j|$

(F) $Y_j = 1$ $\iff$ $x$ lucky in $j$th iteration.

(G) $\Pr[Y_j] = \frac{1}{2}$.

(H) **Observation**: $Y_1, Y_2, \ldots, Y_m$ are independent variables.

(I) $x$ can participate $\leq \rho = \log_{4/3} n \leq 3.5 \ln n$ rounds.

(J) $\ldots$since $|S_j| \leq n(3/4)^j$ # of lucky iteration in $1 \ldots j$.

(K) If $\rho$ lucky rounds in first $k$ rounds $\implies |S_k| \leq (3/4)^\rho n \leq 1$.

10.4.3 Proving that an element...

10.4.3.1 ... participates in small number of rounds.

(A) Brain reset!
(B) Q: How many rounds $x$ participates in = how many coin flips till one gets $\rho$ heads?
(C) A: In expectation, $2\rho$ times.

10.4.4 Proving that an element...

10.4.4.1 ... participates in small number of rounds.

(A) Assume the following:

**Lemma 10.4.1.** In $M$ coin flips: $\Pr[\#\ heads \leq M/4] \leq \exp(-M/8)$.

(B) Set $M = 32 \ln n \geq 8\rho$.
(C) $\Pr[Y_j = 0] = \Pr[Y_j = 1] = 1/2$.
(D) $Y_1, Y_2, \ldots, Y_M$ are independent.
(E) $\implies$ probability $\leq \rho \leq M/4$ ones in $Y_1, \ldots, Y_M$ is

$\leq \exp \left( -\frac{M}{8} \right) \leq \exp(-\rho) \leq \frac{1}{n^3}$.

(F) $\implies$ probability $x$ participates in $M$ recursive calls of QuickSort $\leq 1/n^3$.

10.4.5 Proving that an element...

10.4.5.1 ... participates in small number of rounds.

(A) $n$ input elements. Probability depth of recursion in QuickSort $> 32 \ln n$ is $\leq (1/n^3) \times n = 1/n^2$.
(B) Result:
Theorem 10.4.2. With high probability (i.e., $1 - 1/n^2$) the depth of the recursion of QuickSort is $\leq 32 \ln n$. Thus, with high probability, the running time of QuickSort is $O(n \log n)$.

(C) Same result holds for MatchNutsAndBolts.

10.4.5.2 Alternative proof of high probability of QuickSort

(A) $T$: $n$ items to be sorted.
(B) $t \in T$: element.
(C) $X_i$: the size of subproblem in $i$th level of recursion containing $t$.
(D) $X_0 = n$, and $E[X_i | X_{i-1}] \leq \frac{7}{8} X_{i-1} + \frac{1}{2} X_{i-1} \leq \frac{7}{8} X_{i-1}$.
(E) $\forall$ random variables $E[X] = E_y[E[X | Y = y]]$.
(F) $E[X_i] = E_y[E[X_i | X_{i-1} = y]] \leq E_{X_{i-1}=y} \left( \frac{7}{8} y \right) \leq \frac{7}{8} E[X_{i-1}] \leq \left( \frac{7}{8} \right)^i E[X_0] = \left( \frac{7}{8} \right)^i n$.

10.4.5.3 Alternative proof of high probability of QuickSort

(A) $M = 8 \log_8/n$: $\mu = E[X_M] \leq \left( \frac{7}{8} \right)^M n \leq \frac{1}{n^7} n = \frac{1}{n^7}$.
(B) Markov’s Inequality: For a non-negative variable $X$, and $t > 0$, we have:
$$\Pr[X \geq t] \leq \frac{E[X]}{t}.$$  

(C) By Markov’s inequality:
$$\Pr[t \text{ participates} > M \text{ recursive calls}] \leq \Pr[X_M \geq 1] \leq \frac{E[X_M]}{1} \leq \frac{1}{n^7}.$$  

(D) Probability any element of input participates $> M$ recursive calls $\leq n(1/n^7) \leq 1/n^6$.

10.5 Chernoff inequality

10.5.0.4 Preliminaries

(A) $X, Y$: Random variables are independent if $\forall x, y$:
$$\Pr[(X = x) \cap (Y = y)] = \Pr[X = x] \cdot \Pr[Y = y].$$  

(B) The following is easy to prove:

Claim 10.5.1. If $X$ and $Y$ are independent
$$\implies E[XY] = E[X]E[Y].$$  
$$\implies Z = e^X \text{ and } W = e^Y \text{ are independent}.$$  

10.5.0.5 Chernoff inequality

Theorem 10.5.2 (Chernoff inequality). $X_1, \ldots, X_n$: $n$ independent random variables, such that $\Pr[X_i = 1] = \Pr[X_i = -1] = \frac{1}{2}$, for $i = 1, \ldots, n$. Let $Y = \sum_{i=1}^n X_i$. Then, for any $\Delta > 0$, we have
$$\Pr[Y \geq \Delta] \leq \exp \left( -\Delta^2 / 2n \right).$$
10.5.0.6 Proof of Chernoff inequality

Fix arbitrary $t > 0$:

$$\Pr[Y \geq \Delta] = \Pr[tY \geq t\Delta] = \Pr[\exp(tY) \geq \exp(t\Delta)]$$

$$\leq \frac{\mathbb{E}[\exp(tY)]}{\exp(t\Delta)},$$

10.5.1 Proof of Chernoff inequality

10.5.1.1 Continued...

$$\mathbb{E}[\exp(tX_i)] = \frac{1}{2} e^t + \frac{1}{2} e^{-t} = e^t + e^{-t}$$

$$= \frac{1}{2} \left( 1 + \frac{t}{1!} + \frac{t^2}{2!} + \frac{t^3}{3!} + \cdots \right) + \frac{1}{2} \left( 1 - \frac{t}{1!} + \frac{t^2}{2!} - \frac{t^3}{3!} + \cdots \right)$$

$$= 1 + \frac{t^2}{2!} + \cdots + \frac{t^{2k}}{(2k)!} + \cdots.$$}

However: $(2k)! = k!(k+1)(k+2) \cdots 2k \geq k!2^k$.

$$\mathbb{E}[\exp(tX_i)] = \sum_{i=0}^{\infty} \frac{t^{2i}}{(2i)!} \leq \sum_{i=0}^{\infty} \frac{t^{2i}}{2^i(i!)^2} \leq \sum_{i=0}^{\infty} \frac{1}{i!} \left( \frac{t^2}{2} \right)^i = \exp\left( \frac{t^2}{2} \right).$$

$$\mathbb{E}[\exp(tY)] = \mathbb{E}\left[ \exp\left( \sum_i tX_i \right) \right] = \prod_i \mathbb{E}\left[ \exp(tX_i) \right] = \prod_i \mathbb{E}\left[ \exp\left( \frac{t^2}{2} \right) \right] = \exp\left( \frac{nt^2}{2} \right).$$

$$\Pr[Y \geq \Delta] \leq \frac{\mathbb{E}[\exp(tY)]}{\exp(t\Delta)} \leq \frac{\exp\left( \frac{nt^2}{2} \right)}{\exp(t\Delta)} = \exp\left( \frac{nt^2}{2} - t\Delta \right).$$

Set $t = \Delta/n$:

$$\Pr[Y \geq \Delta] \leq \exp\left( \frac{n}{2} \left( \frac{\Delta}{n} \right)^2 - \frac{\Delta}{n} \Delta \right) = \exp\left( -\frac{\Delta^2}{2n} \right).$$

10.5.2 Chernoff inequality...

10.5.2.1 ...what it really says

By theorem:

$$\Pr[Y \geq \Delta] = \sum_{i=\Delta}^{n} \Pr[Y = i] = \sum_{i=n/2+\Delta/2}^{n} \frac{(n)}{2^n} \leq \exp\left( -\frac{\Delta^2}{2n} \right).$$
10.5.3 Chernoff inequality...

10.5.3.1 symmetry

**Corollary 10.5.3.** Let $X_1, \ldots, X_n$ be $n$ independent random variables, such that $\Pr[X_i = 1] = \Pr[X_i = -1] = \frac{1}{2}$, for $i = 1, \ldots, n$. Let $Y = \sum_{i=1}^{n} X_i$. Then, for any $\Delta > 0$, we have

$$\Pr[|Y| \geq \Delta] \leq 2 \exp\left(-\frac{\Delta^2}{2n}\right).$$

10.5.3.2 Chernoff inequality for coin flips

$X_1, \ldots, X_n$ be $n$ independent coin flips, such that $\Pr[X_i = 1] = \Pr[X_i = 0] = \frac{1}{2}$, for $i = 1, \ldots, n$. Let $Y = \sum_{i=1}^{n} X_i$. Then, for any $\Delta > 0$, we have

$$\Pr\left[\frac{n}{2} - Y \geq \Delta\right] \leq \exp\left(-\frac{2\Delta^2}{n}\right) \quad \text{and} \quad \Pr\left[Y - \frac{n}{2} \geq \Delta\right] \leq \exp\left(-\frac{2\Delta^2}{n}\right).$$

In particular, we have $\Pr\left[Y - \frac{n}{2} \geq \Delta\right] \leq 2 \exp\left(-\frac{2\Delta^2}{n}\right)$.

10.5.3.3 The special case we needed

**Lemma 10.5.4.** In a sequence of $M$ coin flips, the probability that the number of ones is smaller than $L \leq M/4$ is at most $\exp(-M/8)$.

**Proof:** Let $Y = \sum_{i=1}^{m} X_i$ the sum of the $M$ coin flips. By the above corollary, we have:

$$\Pr[Y \leq L] = \Pr\left[\frac{M}{2} - Y \geq \frac{M}{2} - L\right] = \Pr\left[\frac{M}{2} - Y \geq \Delta\right],$$

where $\Delta = M/2 - L \geq M/4$. Using the above Chernoff inequality, we get $\Pr[Y \leq L] \leq \exp\left(-\frac{2\Delta^2}{M}\right) \leq \exp(-M/8)$.

10.6 The Chernoff Bound — General Case

10.6.1 The Chernoff Bound

10.6.1.1 The general problem

**Problem 10.6.1.** Let $X_1, \ldots, X_n$ be $n$ independent Bernoulli trials, where

$$\Pr[X_i = 1] = p_i \quad \text{and} \quad \Pr[X_i = 0] = 1 - p_i,$$

and let denote

$$Y = \sum_{i} X_i \quad \mu = \mathbb{E}[Y].$$

**Question:** what is the probability that $Y \geq (1 + \delta)\mu$. 


10.6.2 The Chernoff Bound

10.6.2.1 The general case

Theorem 10.6.2 (Chernoff inequality). For any $\delta > 0$,

$$\Pr[Y > (1 + \delta)\mu] < \left( \frac{e^\delta}{(1 + \delta)^{1+\delta}} \right)^\mu.$$

Or in a more simplified form, for any $\delta \leq 2e - 1$,

$$\Pr[Y > (1 + \delta)\mu] < \exp\left(-\mu\delta^2/4\right),$$

and

$$\Pr[Y > (1 + \delta)\mu] < 2^{-\mu(1+\delta)},$$

for $\delta \geq 2e - 1$.

10.6.2.2 Theorem

Theorem 10.6.3. Under the same assumptions as the theorem above, we have

$$\Pr[Y < (1 - \delta)\mu] \leq \exp\left(-\mu\frac{\delta^2}{2}\right).$$

10.7 Treaps

10.8 Treaps

10.8.0.3 Balanced binary search trees...

(A) Work usually by storing additional information.
(B) Idea: For every element $x$ inserted
    randomly choose priority $p(x) \in [0, 1]$.
(C) $X = \{x_1, \ldots, x_n\}$
    priorities: $p(x_1), \ldots, p(x_n)$.
(D) $x_k$: lowest priority in $X$.
(E) Make $x_k$ the root.
(F) partition $X$ in the natural way:
    (A) $L$: set of all the numbers smaller than $x_k$ in $X$, and
    (B) $R$: set of all the numbers larger than $x_k$ in $X$.

10.8.0.4 Treaps

Continuing recursively, we have:

(A) $L$: set of all the numbers smaller than $x_k$ in $X$, and
(B) $R$: set of all the numbers larger than $x_k$ in $X$. 
**Definition 10.8.1.** Resulting tree a *treap.*

Tree over the elements, and a heap over the priorities; that is, 
\[
\text{TREAP} = \text{TREE} + \text{HEAP}.
\]

**10.8.0.5 Treaps continued**

**Lemma 10.8.2.** $S$: $n$ elements.

Expected depth of treap $T$ for $S$ is $O(\log(n))$.

Depth of treap $T$ for $S$ is $O(\log(n))$ w.h.p.

**Proof:** QuickSort...  

**10.8.1 Operations**

**10.8.1.1 Treaps - implementation**

**Observation 10.8.3.** Given $n$ distinct elements, and their (distinct) priorities, the treap storing them is uniquely defined.

**10.8.1.2 Rotate right...**

**10.8.1.3 Insertion**

**10.8.1.4 Treaps – insertion**

(A) $x$: an element $x$ to insert.
(B) Insert it into $T$ as a regular binary tree.
(C) Takes $O(\text{height}(T))$.
(D) $x$ is a leaf in the treap.
(E) Pick priority $p(x) \in [0, 1]$.
(F) Valid search tree, but priority heap is broken at $x$.
(G) Fix priority heap around $x$.  

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10.8.1.5 Fix treap for a leaf $x$...

\[
\text{RotateUp}(x) \\
\quad y \leftarrow \text{parent}(x) \\
\quad \text{while } p(y) > p(x) \text{ do} \\
\quad \quad \text{if } y.\text{left}_\text{child} = x \text{ then} \\
\quad \quad \quad \text{RotateRight}(y) \\
\quad \quad \text{else} \\
\quad \quad \quad \text{RotateLeft}(y) \\
\quad y \leftarrow \text{parent}(x)
\]

Insertion takes $O(\text{height}(T))$.

10.8.1.6 Treaps – deletion

(A) Deletion is just an insertion done in reverse.
(B) $x$: element to delete.
(C) Set $p(x) \leftarrow +\infty$.
(D) rotate $x$ down till its a leaf.
(E) Rotate so that child with lower priority becomes new parent.
(F) $x$ is now leaf – deleting is easy...

10.8.1.7 Split

(A) $x$: element stored in treap $T$.
(B) split $T$ into two treaps – one treap $T_{\leq x}$ and treap $T_{> x}$ for all the elements larger than $x$.
(C) Set $p(x) \leftarrow -\infty$.
(D) fix priorities by rotation.
(E) $x$ item is now the root.
(F) Splitting is now easy....
(G) Restore $x$ to its original priority. Fix by rotations.

10.8.1.8 Meld

(A) $T_L$ and $T_R$: treaps.
(B) all elements in $T_L$ ¡ all elements in $T_R$.
(C) Want to merge them into a single treap...

10.8.1.9 Treap – summary

Theorem 10.8.4. Let $T$ be an empty treap, after a sequence of $m = n^c$ insertions, where $c$ is some constant.

\[d: \text{arbitrary constant.}\]

The probability depth $T$ ever exceed $d \log n$ is $\leq 1/n^{O(1)}$.

A treap can handle insertion/deletion in $O(\log n)$ time with high probability.

10.8.1.10 Proof

Proof: (A) $T_1, \ldots, T_m$: sequence of treaps.
(B) $T_i$ is treap after $i$th operation.
(C) $\alpha_i = \Pr[\text{depth}(T_i) > tc' \log n] = \Pr[\text{depth}(T_i) > c't\left(\frac{\log n}{\log |T_i|}\right) \cdot \log |T_i|] \leq \frac{1}{n^{O(1)}}$.
(D) Use union bound...
10.8.1.11 Bibliographical Notes

(A) Chernoff inequality was a rediscovery of Bernstein inequality.
(B) ...published in 1924 by Sergei Bernstein.
(C) Treaps were invented by Siedel and Aragon ?.
(D) Experimental evidence suggests that Treaps performs reasonably well in practice see ?.
(E) Old implementation of treaps I wrote in C is available here: http://valis.cs.uiuc.edu/blog/?p=6060