Based on earlier notes by Alistair Sinclair

1 Large deviations in coin-tossing, and an application to routing in networks

Consider a sequence of n independent tosses of a coin with heads probability p. The expected number of heads is $\mu = np$. What is the probability that the number of heads deviates a lot from this? Specifically, what is the probability that it lies outside the range $(1 \pm \delta)\mu$?

Actually, we'll be a bit more general and let each coin toss have its own heads probability p_i. Define $X_i = \begin{cases} 1 & \text{if the } i\text{th toss is heads;} \\ 0 & \text{otherwise.} \end{cases}$

Thus the number of heads is $X = \sum_{i=1}^{n} X_i$.

Clearly $\mathrm{E}(X_i) = p_i$ and $\mathrm{Var}(X_i) = p_i(1-p_i)$. Hence $\mu = \mathrm{E}(X) = \sum_i p_i$ and, <u>since the X_i are independent</u>, $\sigma^2 = \mathrm{Var}(X) = \sum_i \mathrm{Var}(X_i) = \sum_i p_i(1-p_i)$.

Chebyshev's inequality gives us a bound on the probability that X deviates from its expectation:

$$\Pr[|X-\mu| \ge \delta\mu] \le \frac{\mathrm{Var}(X)}{\delta^2\mu^2} = \frac{\sum_i p_i(1-p_i)}{\delta^2\mu^2} \le \frac{\mu}{\delta^2\mu^2} = \frac{1}{\delta^2\mu}. \qquad (*)$$

This bound, however, is rather weak. A much stronger one is given by <u>Chernoff's bound</u>, whose proof we omit. (If you are interested, see e.g. Section 4.1 of Motwani & Raghavan.) This is probably the most widely used inequality in the analysis of sophisticated randomized algorithms today.

Theorem 1 [Chernoff's Bound]

1. $\Pr[X \le (1-\delta)\mu] \le \mathrm{e}^{-\delta^2\mu/2}$ *for all* $0 < \delta < 1$.
2. $\Pr[X \ge (1+\delta)\mu] \le \begin{cases} \mathrm{e}^{-\delta^2\mu/3} & \textit{for all } 0 < \delta < 1; \\ \mathrm{e}^{-\delta^2\mu/(2+\delta)} & \textit{for all } \delta \ge 1. \end{cases}$ □

Note that we don't need to consider $\delta \ge 1$ in case 1. (Why?)

Putting the two bounds in the theorem together, we get:

$$\Pr[|X-\mu| \ge \delta\mu] \le 2\mathrm{e}^{-\delta^2\mu/3} \qquad \text{for all } 0 < \delta < 1$$

(and something of similar form for $\delta \ge 1$ in case 2). Compare this with the bound from Chebyshev: it is <u>much</u> stronger, since μ appears as a negative exponential rather than just as a denominator. (However, you should remember that Chernoff's bound applies only to *independent* coin tosses, while Chebyshev is valid always.)

Section 4.2 from Motwani & Raghavan describes a typical application of Chernoff's bound. The example problem is that of *routing on a hypercube*. Chernoff's bound is used crucially in the analysis at the top of page 78. Here, the coin tosses[1] are the r.v.'s H_{ij} (with i fixed and $j = 1, \ldots, N$), so we are interested in the r.v. $X = \sum_{j=1}^{N} H_{ij}$. Now $\mu = \mathrm{E}\,(X) \leq \frac{n}{2}$, and we want a bound on $\Pr[X \geq 6n]$. Clearly the worst case is $\mu = \frac{n}{2}$, so we take $\delta = 11$. Now case 2 of Chernoff's bound gives us $\Pr[X \geq 6n] \leq \mathrm{e}^{-121\mu/13} = \mathrm{e}^{-121n/26} < 2^{-6n}$, as claimed by Motwani & Raghavan.

Ex: After understanding the analysis of randomized routing, convince yourself that the analysis <u>would not work</u> using just the Chebyshev bound. $\square$

There are several alternative versions of the Chernoff bound. The following one is useful when we do not know the expectation μ.

Theorem 2 [Chernoff's Bound – Second Version]

1. $\Pr[X \leq \mu - \delta n] \leq \mathrm{e}^{-2\delta^2 n}$ *for all* $0 < \delta < \mu$.
2. $\Pr[X \geq \mu + \delta n] \leq \mathrm{e}^{-2\delta^2 n}$ *for all* $0 < \delta < 1$.

[1] Motwani & Raghavan use the term "Poisson trials" for independent coin tosses.