Min-Wise independent linear permutations

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January 13, 2000

1 Introduction

Broder, Charikar, Frieze and Mitzenmacher [3] introduced the notion of a set of min-wise independent permutations. We say that $\mathcal{F} \subseteq S_n$ is *min-wise independent* if for any set $X \subseteq [n]$ and any $x \in X$, when π is chosen at random in $\mathcal{F}$ we have

$$\mathbb{P}(\min\{\pi(X)\} = \pi(x)) = \frac{1}{|X|}. \tag{1}$$

The research was motivated by the fact that such a family (under some relaxations) is essential to the algorithm used in practice by the AltaVista web index software to detect and filter near-duplicate documents. A set of permutations satisfying (1) needs to be exponentially large [3]. In practice we can allow certain relaxations. First, we can accept small relative errors. We say that $\mathcal{F} \subseteq S_n$ is *approximately min-wise independent with relative error* ϵ (or just approximately min-wise independent, where the meaning is clear) if for any set $X \subseteq [n]$ and any $x \in X$, when π is chosen at random in $\mathcal{F}$ we have

$$\left| \mathbb{P}\big(\min\{\pi(X)\} = \pi(x)\big) - \frac{1}{|X|} \right| \leq \frac{\epsilon}{|X|}. \tag{2}$$

In other words we require that all the elements of any fixed set X have only an almost equal chance to become the minimum element of the image of X under π.

Linear permutations are an important class of permutations. Let p be a (large) prime and let $\mathcal{F}_p = \{\pi_{a,b} :\ 1 \leq a \leq p-1,\ 0 \leq b \leq p-1\}$ where for $x \in [p] = \{0, 1, \ldots, p-1\}$,

$$\pi_{a,b}(x) = ax + b \bmod p,$$

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where for integer n we define $n \bmod p$ to be the non-negative remainder on division of n by p.

For $X \subseteq [p]$ we let

$$F(X) = \max_{x \in X} \{\mathbb{P}_{a,b}(\min\{\pi(X)\} = \pi(x))\}$$

where $\mathbb{P}_{a,b}$ is over π chosen uniformly at random from $\mathcal{F}_p$. The natural questions to discuss are what are the extremal and average values of $F(X)$ as X ranges over $\mathcal{A}_k = \{X \subseteq [p] : |X| = k\}$. The following results were some of those obtained in [3]:

Theorem 1
(a) *Consider the set $X_k = \{0, 1, 2 \ldots k-1\}$, as a subset of $[p]$. As $k, p \to \infty$, with $k^2 = o(p)$,*

$$\mathbb{P}_{a,b}(\min\{\pi(X_k)\} = \pi(0)) = \frac{3}{\pi^2} \frac{\ln k}{k} + O\left(\frac{k^2}{p} + \frac{1}{k}\right).$$

(b) *As $k, p \to \infty$, with $k^4 = o(p)$,*

$$\frac{1}{2(k-1)} \leq \mathbb{E}_X[F(X)] \leq \frac{\sqrt{2}+1}{\sqrt{2}k} + O\left(\frac{1}{k^2}\right),$$

where $\mathbb{E}_X$ denotes expectations over X chosen uniformly at random from $\mathcal{A}_k$.

In this paper we improve the second result and prove

Theorem 2
As $k, p \to \infty$,

$$\mathbb{E}_X[F(X)] = \frac{1}{k} + O\left(\frac{(\log k)^3}{k^{3/2}}\right).$$

Thus for most sets, simply chosen, random linear permutations, will suffice as (near) min-wise independent. Other results on min-wise independence have been obtained by Indyk [6], Broder, Charikar and Mitzenmacher [4] and Broder and Feige [5].

2 Proof of Theorem 2

Let $X = \{x_0, x_1, \ldots, x_{k-1}\} \subseteq [p]$. Let $\beta_i = ax_i \bmod p$ for $i = 0, 1, \ldots, k-1$. Let

$$i = i(X, a) = \min\{\beta_0 - \beta_j \bmod p : \ j = 1, 2, \ldots, k-1\}. \tag{3}$$

Let

$$A_i = A_i(X) = \{a \in [p] : \ i(X, a) = i\}$$

and note that

$$|A_i| \leq k-1, \qquad i=1,2,\ldots,p-1.$$

Then

$$\min\{\pi(X)\} = \pi(x_0) \text{ iff } 0 \in \{\beta_0+b, \beta_0+b-1,\ldots,\beta_0+b-i+1\} \bmod p.$$

Thus if

$$Z = Z(X) = \sum_{i=1}^{p-1} i|A_i|,$$

$$\mathbb{P}_{a,b}(\min\{\pi(X)\} = \pi(x_0)) = \frac{Z}{p(p-1)}. \tag{4}$$

Fix $a \in \{1,2,\ldots,p-1\}$ and x_0. Then

$$\mathbb{P}(a \in A_i) = (k-1)\cdot\frac{1}{p-1}\prod_{t=1}^{k-2}\left(1-\frac{i+t}{p-1-t}\right) \tag{5}$$

We write $Z = Z_0 + Z_1$ where $Z_0 = \sum_{i=1}^{i_0} i|A_i|$ where $i_0 = \frac{4p\log k}{k}$. Now, by symmetry,

$$\mathbb{E}_X(\mathbb{P}_{a,b}(\min\{\pi(X)\} = \pi(x_0)) = \frac{1}{k} \tag{6}$$

and so

$$\mathbb{E}_X(Z) = \frac{p(p-1)}{k}.$$

It follows from (5) that

$$\begin{aligned}\mathbb{E}(Z_1) &\leq (k-1)\sum_{i=i_0+1}^{p-1} i\exp\left\{-\frac{4(k-2)\log k}{k}\right\} \\ &\leq \frac{p^2}{k^3}\end{aligned} \tag{7}$$

for large k, p.

We continue by using the Azuma-Hoeffding Martingale tail inequality – see for example [1, 2, 7, 8, 9]. Let x_0 be fixed and for a given X let $\hat{X}$ be obtained from X by replacing x_j by randomly chosen $\hat{x}_j$. For $j \geq 1$ let

$$d_j = \max_X\{|\mathbb{E}_{\hat{x}_j}(Z(X) - Z(\hat{X}))|\}.$$

Then for any $t > 0$ we have

$$\mathbb{P}(|Z_0 - \mathbb{E}(Z_0)| \geq t) \leq 2\exp\left\{-\frac{2t^2}{d_1^2+\cdots+d_{k-1}^2}\right\}. \tag{8}$$

We claim that

$$d_j \leq \sum_{i=1}^{i_0} i + \sum_{i=1}^{i_0} \frac{(k-1)i^2}{p} \tag{9}$$

$$\leq \frac{i_0^2}{2} + \frac{i_0^3 k}{3p} + O(p)$$

$$\leq \frac{30(\log k)^3 p^2}{k^2} \tag{10}$$

Explanation for (9): If $a \in A_i(X)$ because $ax_j = ax_0 - i \bmod p$ then changing x_j to $\hat{x}_j$ changes $|A_i|$ by one. This explains the first summation. The second accounts for those $a \in A_i(X)$ for which $ax_0 - a\hat{x}_j \bmod p < i$, changing the minimum in (3). We then use $|A_i| \leq k-1$ and $\mathbb{P}(ax_0 - a\hat{x}_j \bmod p < i) = \frac{i}{p}$.

Using (10) in (8) with $t = \varepsilon \frac{p^2}{k}$ we see that

$$\mathbb{P}\left(|Z_0 - \mathbb{E}(Z_0)| \geq \varepsilon \frac{p^2}{k}\right) \leq \exp\left\{-\frac{\varepsilon^2 k}{450(\log k)^6}\right\}.$$

It now follows from (4), (6), (7) and the above that

$$\mathbb{E}_X[F(X)] = \frac{1}{k} + O\left(\frac{1}{k^2} + \frac{1}{k}\int_{\varepsilon=0}^{\infty} \min\left\{1, k\exp\left\{-\frac{\varepsilon^2 k}{450(\log k)^6}\right\}\right\} d\varepsilon\right)$$

and the result follows. □

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This research was sponsored in part by National Science Foundation (NSF) grant no. CCR-0122581.