PCP - Huji Course, Ex 1.

David Ponarovsky

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1 Ex 1.

Let A be a random matrix in $M(\mathbb{F}_2^{k\times n})$. For any non-zero $x \in \mathbb{F}$, we have that Ax is distributed uniformly.

Claim 1.

Proof. By the fact that $x \neq 0$, there exists at least one coordinate $i \in [k]$ such that $x_i \neq 0$. Thus, we have

$$\begin{aligned}(Ax)_j &= \sum_k A_{jk}x_k = \sum_{i\neq k} A_{jk}x_k + A_{ji}x_i \\ &= \sum_{i\neq k} A_{jk}x_k + A_{ji}\end{aligned}$$

Notice that due to the fact that $\mathbb{F}_2$ is a field, there is exactly one assignment that satisfies the equation conditioned on all the values A_{jk} where $j \neq k$.

$$\begin{aligned}\mathbf{Pr}\left[(Ax)_j = 1\right] &= \sum_{A_{jk};k\neq i} \mathbf{Pr}\left[(Ax)_j = 1 \mid A_{jk}; k \neq i\right] \mathbf{Pr}\left[A_{jk}; k \neq i\right] \\ &= \frac{1}{2}\end{aligned}$$

Therefore, any coordinate of Ax is distributed uniformly $\Rightarrow$ Ax is distributed uniformly. $\square$

By the uniformity of Ax, we obtain that the expected Hamming weight of Ax is:

$$\mathbf{E}\left[|Ax|\right] = \mathbf{E}\left[\sum_i^n (Ax)_i\right] = \frac{1}{2}n$$

As the coordinates of A_x are independent (each row of A is sampled separately), we can use the Hoff's bound to conclude that:

$$\mathbf{Pr}\left[\left||Ax| - \mathbf{E}\left[|Ax|\right]\right| \geq \left(\frac{1}{2} - \delta\right) n\right] \leq e^{-n\left(\frac{1}{2}-\delta\right)^2}$$

Now, we will use the union bound to show that any $x \in \mathbb{F}_2^k$, Ax is of weight at least δ.

$$\mathbf{Pr}\left[|Ax| \geq \delta : \forall x \in \mathbb{F}_2^k\right] \geq 1 - |\mathbb{F}_2^k| \cdot e^{-n\left(\frac{1}{2}-\delta\right)^2}$$

Denote $k = \rho n$ and notice that the above holds when $\rho \geq \left(\frac{1}{2} - \delta\right)^2$.

2 Ex 2.

Claim 2. *Let $v_1, v_2, \ldots, v_m$ be unit vectors in an inner-product space such that $\langle v_i, v_j \rangle \leq -2\varepsilon$ for all $i \neq j$, then $m \leq \frac{1}{2\varepsilon} + 1$.*

Proof. Let us bound the norm of the summation $|\sum_i v_i|$ from both sides. As the norm is non-negative by definition, we will bound it from the left by 0. On the other hand, we have that:

$$0 \leq |\sum_{v_i} v_i| = m + 2\sum_{i,j} \langle v_i, v_j \rangle \leq m - 2 \cdot \frac{m\,(m-1)}{2} \cdot 2\varepsilon$$

Thus, we obtain $m\,(2(m-1)\varepsilon - 1) \leq 0$, namely, $m \leq \frac{1}{2\varepsilon} + 1$ $\square$

Now, define the following product for $u, v \in \mathbb{F}_2^n$, $\langle v, u \rangle = \sum_i (-1)^{v_i} (-1)^{\bar{u}_i}$ and observe that:

1. $\langle v, v \rangle = \sum_i 1 = n \geq 0$.
2. $\langle v, u \rangle = \langle u, v \rangle$.
3. $\langle ax + by, z \rangle = (-1)^a \langle x, z \rangle + (-1)^b \langle y, z \rangle$.

Now, if the v's correspond to a code with distance at least d, then, for any codewords v and u that disagree on at least d coordinates, we have that $\langle v, u \rangle \leq$ `agree`$-$ `disagree = n - 2 disagree` $= n - 2d$. Now consider the normal codewords $\tilde{v_1}..\tilde{v_n}$ and assume that

$$\langle \tilde{v_i}, \tilde{v_j} \rangle = (1 - 2\delta) = \frac{1}{n}\,(n - 2d(v_i, v_j)) \leq \varepsilon$$

Therefore, if $d \geq \frac{1}{2} + \varepsilon$, we obtain the condition of the above claim.

3 Ex 3.

Consider the following process for decoding a,

for $t \in [\tau]$ **do**
  for $i \in [n]$ **do**
    $x \sim_u \mathbb{F}_2^n$
    $a_i^{(t)} \leftarrow w\,(x) + w\,(\sigma_i(x))$
  end
end
for $i \in [n]$ **do**
  $\hat{a}_i \leftarrow [\frac{1}{\tau} \sum_t^\tau a_i^{(t)}]$
end
return $\hat{a}_0, \hat{a}_1, \hat{a}_2..\hat{a}_n$

Claim 3. *For $\tau = \Omega\left(\frac{1}{\varepsilon^4} \log(n)\right)$ The above decoding success to decode $w\,(x)$ with probability $\geq 1 - \frac{1}{n}$.*

Proof. In this question we will say that w agree on $x, \sigma_i(x)$ if both $x, \sigma_i(x)$ were either filliped or unflipped. Clearly if $w(x)$ agree with $w(\sigma_i(x))$ than

$$\begin{aligned} w\,(x) + w\,(\sigma_i(x)) &= H_a(x) + H_a(\sigma_i(x)) \\ &= \sum_{i \neq j} a_j(x_j + x_j) + a_i(x_j + 1 + x_j) = a_j \quad (\text{ neither of them were flipped. }) \\ &= 1 + H_a(x) + 1 + H_a(\sigma_i(x)) = a_i \quad (\text{ both flipped.}) \end{aligned}$$

Thus we can bound the probability that $w\,(x) + w\,(\sigma_i(x)) \neq a_{_i}$ by the probability that w disagree on x and that append at probability:

$$\xi := (1 - f(x))\, f(\sigma_i(x)) + (1 - f(\sigma_i(x)))\, f(x)$$

Now as we want bound ξ we could think about the maximization problem under the restrictions that $f(x), f(\sigma_i(x) \leq \frac{1}{2} - \varepsilon$. We know that the maximum lay on the boundary so we can assign $\frac{1}{2} - \varepsilon$ for each of the probabilities to obtain an upper bound. That will yield $\xi \leq 2 \cdot \left(\frac{1}{2} - \varepsilon\right)\left(\frac{1}{2} + \varepsilon\right)$, namely $\xi \leq \frac{1}{2} - 2\varepsilon^2$. Now the probability that a coordinate i will rounded to the opposite side, that it $\hat{a}_i \neq a_i$ mean that arithmetic mean over τ experiments were $2\varepsilon^2$ far from the expectation. Which by Hoff' bound is bounded by: $e^{\tau 4\varepsilon^4}$. So using the union bound we obtain:

$$\mathbf{Pr}\left[\text{ decoding success }\right] \geq 1 - n \cdot e^{\tau 4\varepsilon^4}$$

Therefore it's enough to take $\tau = O(\frac{1}{\varepsilon^4}\log(n))$ to obtain a decoder which run at time $O(\frac{1}{\varepsilon^4} n \log(n))$ and success with heigh probability. □

4 Ex 3.

Consider the following process for decoding a:

for $t \in [\tau]$ **do**
  for $i \in [n]$ **do**
    $x \sim_u \mathbb{F}_2^n$
    $a_i^{(t)} \leftarrow w(x) + w(\sigma_i(x))$
  end
end
for $i \in [n]$ **do**
  $\hat{a}_i \leftarrow [\frac{1}{\tau}\sum_t^\tau a_i^{(t)}]$
end
return $\hat{a}_0, \hat{a}_1, \hat{a}_2..\hat{a}_n$

Claim 4. *For $\tau = \Omega\left(\frac{1}{\varepsilon^4}\log(n)\right)$ the above decoding succeeds in decoding $w(x)$ with probability $\geq 1 - \frac{1}{n}$.*

Proof. In this question we will say that w agrees on $x, \sigma_i(x)$ if both $x, \sigma_i(x)$ were either flipped or unflipped. Clearly, if $w(x)$ agrees with $w(\sigma_i(x))$ then

$$\begin{aligned} w(x) + w(\sigma_i(x)) &= H_a(x) + H_a(\sigma_i(x)) \\ &= \sum_{i \neq j} a_j(x_j + x_j) + a_i(x_j + 1 + x_j) = a_j \quad (\text{ neither of them were flipped. }) \\ &= 1 + H_a(x) + 1 + H_a(\sigma_i(x)) = a_i \quad (\text{ both flipped.}) \end{aligned}$$

Thus, we can bound the probability that $w(x) + w(\sigma_i(x)) \neq a_i$ by the probability that w disagrees on x and that is at probability:

$$\xi := (1 - f(x))\, f(\sigma_i(x)) + (1 - f(\sigma_i(x)))\, f(x)$$

Now, to bound ξ, we can think about the maximization problem under the restrictions that $f(x), f(\sigma_i(x) \leq \frac{1}{2} - \varepsilon$. We know that the maximum lies on the boundary, so we can assign $\frac{1}{2} - \varepsilon$ for each of the probabilities to obtain an upper bound. That will yield $\xi \leq 2 \cdot \left(\frac{1}{2} - \varepsilon\right)\left(\frac{1}{2} + \varepsilon\right)$, namely $\xi \leq \frac{1}{2} - 2\varepsilon^2$. Now, the probability that a coordinate i will be rounded to the opposite side, i.e. $\hat{a}_i \neq a_i$, means that the arithmetic mean over τ experiments is $2\varepsilon^2$ far from the expectation. According to Hoff's bound, this is bounded by $e^{\tau 4\varepsilon^4}$. Thus, using the union bound, we obtain:

$$\mathbf{Pr}\left[\text{ decoding success }\right] \geq 1 - n \cdot e^{\tau 4\varepsilon^4}$$

Therefore, it is enough to take $\tau = O(\frac{1}{\varepsilon^4}\log(n))$ to obtain a decoder that runs in time $O(\frac{1}{\varepsilon^4} n \log(n))$ and succeeds with high probability. □

5 Ex 4.

5.1 (a)

We will prove that if for any x, f interpolate well on $x, x+1, .., x+d+1$ than any it interpolate well on every coordinates set at size $d+1$. Denote by $J \subset \mathbb{F}_q$ at size $d+1$. Let's continue by induction on $\max J$. The base case $\max J = d+1 \Rightarrow J = \{1, 2.., d+1\}$ follow straightforwardly from the assumption. Assume the correctness for any J such that $\max J \leq x_0$ and consider J' such that $\max J' = x_0 +$. Now it given that $S = \{x_0 - d, x_0 - d + 1, ..x_0 + 1\}$ is well interpolating set, so there exists coefficients a_1, a_{d+1} such that $a_{d+1} f(x_0+1) = \sum_{x_i \in S/(x_0+1)} a_i f(x_i)$ On the overhand, for ant any $x_i \in S/(x_0+1)$ the union $K = x_i \cup J/(x_0+1)$ is subset of $\mathbb{F}_q$ at size $d+1$ such that $\max K \leq x_0$. Hence by induction assumption K is well interpolating set and we can exchange any $f(x_i)$ for $x_i \in S$ by a linear combination of $f(x_i)$ for $x_i \in J/(x_0+1)$. So in overall we obtain that J is depended set, namely f is well interpolate on J.

5.2 (b)

Define the function $g(x) = f(t^{-1}(x-s))$. Note that q is prime, thus $(\mathbb{F}_q/0, \cdot)$ and $(\mathbb{F}_q, +)$ are groups and the inverse elements $-s, t^{-1}$ are exist and uniqs. Suppose that y is a zero of $g \Rightarrow f(t(y+s)) = g(y) = 0$, Hence the number of zeros of f equals to the number of zeros of g, which means that their degree are equal $\Rightarrow g$ is also a polynomial at degree at most d, $\Rightarrow a_1, a_2..a_d$ are also the interpolation coefficients respecting to the interpolation set $\{tx_1 + s, tx_2 + s, .., tx_d + s\}$.

6 Ex (5).

6.1 (a)

As shown in the previous section, by the fact that q is prime, we have that $g_{u,v}$ acts on $\mathbb{F}_q^m$ by $g_{u,v}(x) = u + vx$, (for any $v \neq 0$). Thus, $f(g_{u,v}(x))$ is just a permutation over the values of f. As the number of zeros remains the same, we have that $f(g_{u,v}(x))$ is also a degree d polynomial. Therefore, the restricted polynomial $f|_L$ corresponds to the restriction L' of another polynomial obtained by taking $u' = 0$ and v to be supported only on a single coordinate. Hence, the restricted polynomial can have at most d zeros.

6.2 (b)

As we have that f is a polynomial of degree exactly d, there must be a monomial $x_1^{d_1} x_2^{d_2} ..x_k^{d_k}$ such that $\sum_i d_i = d$. Denote by g the sum of all those monomials, and by $v \in \mathbb{F}_q^n$ a coordinate on which $g(v) \neq 0$ (if there is no such v, then we could write f as a sum of monomials, each of degree at most $d-1$).

Now, as $g(v), t \neq 0$, we obtain that $g(vt)$ is equal exactly to $t^d \cdot c$ where c is the sum of coefficients of each monomial of g (also $c = g(1)$). As $f(x) - g(x)$ is a polynomial of degree $d-1$, it holds from the previous section that $(f-g)(vt)$ is also a polynomial of degree at most $d-1$. Thus, it cannot zero out $g(vt) \Rightarrow f(vt) = (f-g)(vt) + g(vt)$ is also a polynomial of degree d.

7 Ex (6).

7.1 (a) and (b).

Let F be a function from $\{0, 1..d\}^2 \to \mathbb{F}_q$, we are going to define a d-degree polynomail $f : \mathbb{F}_q^2 \to \mathbb{F}_q$ that agree with F and show that is uniq. Notice that any polynomial could be written as $\sum_{i,j} a_i a_j x^i y^j$. Thus, the assignments of $(d+1)^2$ points define $(d+1)^2$ equations over $(d+1)^2$ variables. In addition, as the determinant of the matrix equals

$$
\begin{bmatrix}
1 & 0 & 0 & 0 & 0^2 \\
1 & 1 & 1\cdot 0 & 0 & 1\cdot 1 \\
1 & 1 & 1 & 1\cdot 1 & 1^2 \\
1 & d & d & d^2 & d^2
\end{bmatrix}
\cdot
\begin{bmatrix}
a_{00} \\ a_{01} \\ a_{10} \\ a_{11} \\ a_{20} \\ a_{dd}
\end{bmatrix}
=
\begin{bmatrix}
F(0,0) \\ F(0,1) \\ F(1,0) \\ F(1,1) \\ F(2,0) \\ F(d,d)
\end{bmatrix}
$$

Figure 1: Illustration of the equations system. The left system is a vadermonde matrix in which the $((x, y), (i, j))$ entry corresponds to $x^i y^j$ where (x, y) are one of the points in $(x, y) \in \{0..d\}^2$.

$$
\begin{aligned}
\sum_{\sigma \in S_n} (-1)^{\sigma(\pi)} \prod_{i,j} (x_i^{\sigma(i)_1} y_j^{\sigma(j)_2}) &= \prod_{i<j} (x_i - x_j) \prod_{i<j} (y_i - y_j) \\
&= \prod_{i<j} (x_i - x_j) \prod_{i<j} (y_i - y_j) = \prod i^{d-i} \prod j^{d-j} \nmid q
\end{aligned}
$$

So the detriment is not zero, thus we can solve that system by gauss elimination and obtain unique solution. The solution is uniq and define the coefficients of f.

7.2 (c).

Now consider a function $f : \mathbb{F}_q^2 \to \mathbb{F}_q$ which any restriction of f to a line is a polynomial at degree at most d.