

Homework 1

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Homework guidelines: You may work with other students, as long as (1) they have not yet solved the problem, (2) you write down the names of all other students with which you discussed the problem, and (3) you write up the solution on your own. No points will be deducted, no matter how many people you talk to, as long as you are honest. It's ok to look up famous sums and inequalities that help you to solve the problem, but don't look up an entire solution. (Note – Much of problem 3 will be easier after the lecture of November 10).

1. The goal of this problem is to carefully prove a lower bound on testing whether a distribution is uniform.
 - (a) For a distribution p over $[n]$ and a permutation π on $[n]$, define $\pi(p)$ to be the distribution such that for all i , $\pi(p)_{\pi(i)} = p_i$.
 Let \mathcal{A} be an algorithm that takes samples from a black-box distribution over $[n]$ as input. We say that \mathcal{A} is *symmetric* if, once the distribution is fixed, the output distribution of \mathcal{A} is identical for any permutation of the distribution.
 Show the following: Let \mathcal{A} be an arbitrary testing algorithm for uniformity. Suppose \mathcal{A} has sample complexity at most $s(n)$, where n is the domain size of the distributions. Then, there exists a symmetric algorithm that tests uniformity with sample complexity at most $s(n)$.
 - (b) Define a *fingerprint* of a sample as follows: Let S be a multiset of at most s samples taken from a distribution p over $[n]$. Let the random variable C_i , for $0 \leq i \leq s$, denote the number of elements that appear exactly i times in S . The collection of values that the random variables $\{C_i\}_{0 \leq i \leq s}$ take is called the *fingerprint* of the sample.
 For example, let $D = \{1..7\}$ and the sample set be $S = \{5, 7, 3, 3, 4\}$. Then, $C_0 = 3$ (elements 1, 2 and 6), $C_1 = 3$ (elements 4, 5 and 7), $C_2 = 1$ (element 3), and $C_i = 0$ for all $i > 2$.
 Show the following: If there exists a symmetric algorithm \mathcal{A} for testing uniformity, then there exist an algorithm for testing uniformity that gets as input only the fingerprint of the sample that \mathcal{A} takes.
 - (c) Show that any algorithm making $o(\sqrt{n})$ queries cannot have the following behavior when given error parameter ϵ and access to samples of a distribution p over a domain D of size n :
 - if $p = U_D$, then \mathcal{A} outputs “pass” with probability at least $2/3$.
 - if $|p - U_D|_1 > \epsilon$, then \mathcal{A} outputs “fail” with probability at least $2/3$.
 - (d) Suppose an algorithm has the following behavior when given error parameter ϵ and access to samples of a distribution p over a domain $D = \{1, \dots, n\}$:
 - if p is monotone, then \mathcal{A} outputs “pass” with probability at least $2/3$.

- if for all monotone distributions q over D , $|p - q|_1 > \epsilon$, then \mathcal{A} outputs “fail” with probability at least $2/3$

Show that this algorithm must make $\Omega(\sqrt{n})$ queries.

Hint: Reduce from the problem of testing uniformity.

- Let p be a distribution over domain S . Let S_1, S_2 be a partition of S . Let $r_1 = \sum_{j \in S_1} p(j)$ and $r_2 = \sum_{j \in S_2} p(j)$. Let the restrictions p_1, p_2 be the distribution p conditioned on falling in S_1 and S_2 respectively – that is, for $i \in S_1$, let $p_1(i) = p(i)/r_1$ and for $i \in S_2$, let $p_2(i) = p(i)/r_2$. For distribution q over domain S , let $t_1 = \sum_{j \in S_1} q(j)$ and $t_2 = \sum_{j \in S_2} q(j)$, and define q_1, q_2 analogously. Suppose that $|r_1 - t_1| + |r_2 - t_2| < \epsilon_1$, $\|p_1 - q_1\|_1 < \epsilon_2$ and $\|p_2 - q_2\|_1 < \epsilon_2$. Show that $\|p - q\|_1 \leq \epsilon_1 + \epsilon_2$.
- This problem concerns testing closeness to a distribution that is entirely known to the algorithm. In the following, assume that p and q are distributions over D . The algorithm is given access to samples of p , and knows an exact description of the distribution q in advance – the query complexity of the algorithm is only the number of samples from p . Assume that $|D| = n$.

- Define $\text{Bucket}(q, D, \epsilon)$ as a partition $\{D_0, D_1, \dots, D_k\}$ of D with $k = (2/\log(1 + \epsilon)) \cdot \log |D|$, $D_0 = \{i \mid q(i) < 1/(|D| \log |D|)\}$, and for all i in $[k]$,

$$D_i = \left\{ j \in D \mid \frac{(1 + \epsilon)^{i-1}}{|D| \log |D|} \leq q(j) < \frac{(1 + \epsilon)^i}{|D| \log |D|} \right\}.$$

Show that if one considers the restriction of q to any of the buckets D_i , then the distribution is close to uniform: i.e., Show that if q is a distribution over D and $\{D_0, \dots, D_k\} = \text{Bucket}(q, D, \epsilon)$, then for $i \in [k]$ we have $|q_{D_i} - U_{D_i}|_1 \leq \epsilon$, $\|q_{D_i} - U_{D_i}\|_2^2 \leq \epsilon^2/|D_i|$, and $q(D_0) \leq 1/\log |D|$.

Hint: it may be helpful to remember that $1/(1 + \epsilon) > 1 - \epsilon$.

- Let $(D_0, \dots, D_k) = \text{Bucket}(q, [n], \epsilon)$. For each i in $[k]$, if $\|p_{D_i}\|_2^2 \leq (1 + \epsilon^2)/|D_i|$ then $|p_{D_i} - U_{D_i}|_1 \leq \epsilon$ and $|p_{D_i} - q_{D_i}|_1 \leq 2\epsilon$.
- Show that for any fixed q , there is an $\tilde{O}(\sqrt{n} \text{poly}(1/\epsilon))$ query algorithm \mathcal{A} with the following behavior:

Given access to samples of a distribution p over domain D , and an error parameter ϵ ,

- if $p = q$, then \mathcal{A} outputs “pass” with probability at least $2/3$.
- if $|p - q|_1 > \epsilon$, then \mathcal{A} outputs “fail” with probability at least $2/3$

- (Don’t turn in) Note that the last problem part generalizes uniformity testing. As a sanity check, what does the algorithm do in the case that $q = U_D$? Also, it is open whether the time complexity of the algorithm can also be made to be $\tilde{O}(\sqrt{n} \text{poly}(1/\epsilon))$ (assume that q is given as an array, in which accessing q_i requires one time step).