Complexity Homework 5

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Problem 1: 2-Universal Hash Function Family.

The first couple of proeblems deal with 2-Universal Hash Function Families.

Define a *hash function family* as a function $\mathcal{H}$of the form $\mathcal{H} : H \times X \to R$, where H is the set of "hash functions" in the family, X is the input space and R the output space of the hash functions. H, X, R are all finite sets. When the family is understood, $\mathcal{H}(h, x) = y$ is often abbreviated as $h(x) = y$. Given an input $x \in X$ we will be interested in hashing it using a *random* $h \in H$.

Call a hash function family *uniform* if for all $x \in X$ and $y \in R$, $\mathbf{Pr}_{h \leftarrow H}[h(x) = y] = \frac{1}{|R|}$. Call a hash function family *pairwise independent* if for all $x_1 \neq x_2 \in X$ and $y_1, y_2 \in R$, $\mathbf{Pr}_{h \leftarrow H}[h(x_1) = y_1 \wedge h(x_2) = y_2] = \mathbf{Pr}_{h \leftarrow H}[h(x_1) = y_1]\,\mathbf{Pr}_{h \leftarrow H}[h(x_2) = y_2]$. Call a hash function family *2-universal* if for all $x_1 \neq x_2 \in X$ and $y_1, y_2 \in R$, $\mathbf{Pr}_{h \leftarrow H}[h(x_1) = y_1 \wedge h(x_2) = y_2] = \frac{1}{|R|^2}$.

Define *maximum collision probability* of a hash function family as $\max_{x_1 \neq x_2 \in X} \mathbf{Pr}_{h \leftarrow H}[h(x_1) = h(x_2)]$.

1. Show a trivial example of a uniform hash function family (use $H = R$) and a trivial example of a pairwise independent hash function family (use $X = R$). Show that a hash function family is uniform *and* pairwise independent if and only if it is 2-universal. Also show that for such a hash function family, the maximum collision probability is $\frac{1}{|R|}$.
2. If $\mathcal{H} : H \times X \to R$, is a uniform hash function family what can you say about the size of H, in terms of $|R|$? What if $\mathcal{H}$is a 2-universal hash function family?
3. A function $f : R \to R'$ is called *regular* if for each $y' \in R'$, $|\{y : f(y) = y'\}| = |R|/|R'|$. Suppose $\mathcal{H} : H \times X \to R$ is a 2-universal hash function family and $f : R \to R'$ is regular. Show that $\mathcal{H}' : H \times X \to R'$, where $\mathcal{H}'(h, x) = f(\mathcal{H}(h, x))$ is 2-universal. Note that this can be used to shrink the output space of a hash function family without affecting the other parameters.
4. A function $f : X' \to X$ is called *one-to-one* if for each $x \in X$, $|\{x' : f(x') = x\}| \leq 1$. Suppose $\mathcal{H} : H \times X \to R$ is a 2-universal hash function family and $f : X' \to X$ is one-to-one. Show that $\mathcal{H}' : H \times X \to R'$, where $\mathcal{H}'(h, x) = \mathcal{H}(h, f(x))$ is 2-universal. Note that this can be used to shrink the input space of a hash function family without affecting the other parameters.

Problem 2:

This problem shows why 2-universal hash function families are useful for the (public-coin) set lower-bound protocol. (See Lecture 15.)

For $S \subseteq X$ and $h : X \to R$, define $h(S) \subseteq R$ as $h(S) = \{h(x) : x \in S\}$. Define $\mathtt{shrink}(h, S) = |S| - |h(S)|$. Note that $\mathtt{shrink}(h, S) \geq 0$. Let $\mathtt{collision}(h, S) = |\{x_1, x_2 \in S : x_1 < x_2 \text{ and } h(x_1) = h(x_2)\}|$.

1. Show that $\mathtt{shrink}(h, S) \leq \mathtt{collision}(h, S)$.
2. Suppose $\mathcal{H} : H \times X \to R$ has a maximum collision probability p. Show that $\mathbf{E}_{h \leftarrow H}[\mathtt{collision}(h, S)] \leq p|S|^2$. Using part (1) conclude that $\mathbf{E}_{h \leftarrow H}[\mathtt{shrink}(h, S)] \leq p|S|^2$.
3. Suppose $\mathcal{H} : H \times X \to R$ is a 2-universal hash function family, then show that for any $T \subseteq X$ such that $|T| = |R|/4$, $\mathbf{E}_{h \leftarrow H}[\mathtt{shrink}(h, T)] \leq \frac{|R|}{16}$.
4. Use this to argue soundness and completeness of the set lower-bound protocol shown in class. Consider for completeness $S \subseteq X$ such that $|S| \geq |R|/4$ and, for soundness $S \subseteq X$ such that $|S| \leq |R|/8$. (Explain clearly what completeness and soundness mean in this context.)

Problem 3:

Show that $\mathbf{FP} \subseteq \sharp\mathbf{P}$. *(Hint: Associate a count with the output of a function, such that the count when written in binary is identical to the original output.)*

Problem 4:

In this problem you will show that $\sharp\mathbf{P} \subseteq \mathbf{FP}^{\mathbf{PP}}$.

An *implicit representation* of a binary string α of length 2^m is a polynomial sized (in m) circuit A^α such that $A^\alpha(i) = \alpha_i$, the i-th bit of α.

1. Consider a binary string α of length 2^m. Your task is to count the number of 1s in the string, in polynomial time (in m). Show how to do this if you are given an oracle T_α, which when given a threshold τ tells you whether the string has more than τ fraction of 1s or not. (That is $T_\alpha(\tau) = 1$ iff α has more than $\tau|\alpha|$ 1s.)
2. Suppose you are given an oracle H_α which can only answer with respect to the threshold $\tau = \frac{1}{2}$, but allows you to give an implicit description of another string β of length 2^m and answers whether the string $\alpha\beta$ has more than $\frac{1}{2}$ 1s in it. (That is $H_\alpha(A^\beta) = 1$ iff the string $\alpha\beta$ has more than $\frac{1}{2}|\alpha\beta|$ 1s.) Show how to implement the oracle T_α using access to the oracle H_α.
3. Consider the language L, such that $L(A^\alpha, A^\beta) = H_\alpha(\beta)$. Show that L is in $\mathbf{PP}$.
4. Conclude that given oracle access to the $\mathbf{PP}$ language L, any function in $\sharp\mathbf{P}$ can be computed in polynomial time. i.e., $\sharp\mathbf{P} \subseteq \mathbf{FP}^L$.

Problem 5 (Extra Credit):

Recall the definition of *alternating threshold Turing Machines* from class (Lecture 17). Given $M_+ = \text{ATTM}[k, (\exists_{\geq r}, \exists), R]$ (i.e. an ATTM with k alternations between thresholds $\exists_{\geq r}$ and $\exists$, and a relation R at the leaves; the degrees of the different $\exists_{\geq r}$ ans $\exists$ configuration nodes are left out of the notation for clarity), with $r > \frac{1}{2}$, define it's complementary ATTM $M_- = \text{ATTM}[k, (\exists_{\geq r}, \forall), \overline{R}]$. Such a pair (M_+, M_-) is said to decide a language L if $x \in L \iff M_+(x) = 1, M_-(x) = 0$ and $x \notin L \iff M_+(x) = 0, M_-(x) = 1$.

Also recall the definition of an AM$[k]$ protocol defined by a verification procedure for Arthur, A (and the lengths of the k messages, alternating between random strings from Arthur and messages from Merlin, starting with one from Arthur). an AM protocol A is said to decide a language L with error probability at most ϵ if $x \in L \iff \max_M \mathbf{Pr}[A \text{ accepts } x \text{ after interacting with } M] \geq 1 - \epsilon$ and $x \notin L \iff \max_M \mathbf{Pr}[A \text{ accepts } x \text{ after interacting with } M] \leq \epsilon$.

1. Given an AM$[k]$ protocol A, define a pair of complementary ATTMs (M_+, M_-) as $M_+ = \text{ATTM}[k, (\exists_{\geq r}, \exists), R]$ and $M_- = \text{ATTM}[k, (\exists_{\geq r}, \forall), \overline{R}])$, (with degrees of the configuration nodes being the message lengths of the protocol to the power of 2) with $R = A$ and $r = \frac{3}{4}$. Show that if A is an AM protocol that decides a language L with error probability at most $2^{-(k+3)}$, then (M_+, M_-) decides L.

   Hint: First try $k = 2$. Consider the protocol's tree, and define the maximum-average acceptance probability for each node (as shown in class). For $x \in L$, using completeness guarantee, what can you say about the fraction of first messages that lead to a node with acceptance probability greater than $1 - 4\epsilon$? For $x \notin L$ use soundness guarantee.
2. Given a pair of complementary ATTMs $(M_+, M_-) = (\text{ATTM}[k, (\exists_{\geq r}, \exists), R], \text{ATTM}[k, (\exists_{\geq r}, \forall), \overline{R}])$, (with degrees of the configuration nodes being powers of 2) define an AM$[k]$ protocol with $A = R$ (and lengths of the messages being logarithms (base 2) of the degrees of the ATTM pair). Show that if (M_+, M_-) decides a language L and if $r \geq 1 - \frac{1}{4k}$, then A_R is an AM protocol that decides L with error probability at most $1/4$.

   Hint: For $x \in L$, using M_+, what can you say about the maximum-acceptance probability of nodes of the constructed protocol's tree. First try $k = 2$. To extend to general k, consider two levels at a time, and use the "union-bound" inequality $(1 - p)^t \geq 1 - pt$.