CPSC 421: Introduction to Theory of Computing
Practice Problem Set #6, Not to be handed in

Note: $\mathbb{N} = \{0, 1, \dots\} \subset \{1, 2, \dots\} = \mathbb{N}_+$. For simplicity (and wlog), the alphabet is $\{0, 1\}$, unless stated otherwise.

1. (Easy) Recall the definition of RP: $L \in \mathsf{RP}$ if there exists a polytime PTM M such that

$$x \in L \Rightarrow \mathbb{P}\big(M(x) = 1\big) \geq 1/2$$
$$x \notin L \Rightarrow \mathbb{P}\big(M(x) = 0\big) = 1.$$

Thus, M errs only when $x \in L$, and the probability of error is at most $1/2$. Now, run M twice on x and accept if at least one of the runs of M on x accepts. *Compute the new error probability and conclude that* $\mathsf{RP} \subset \mathsf{BPP}$.

2. (Medium) Consider the following two definitions of RP:

Definition 1. ($\mathsf{RP1}$): $L \in \mathsf{RP1}$ if there exist a polytime PTM M and a polynomial $p : \mathbb{N} \to \mathbb{N}$, where $p \geq 1$, such that for every $x \in \{0, 1\}^*$

$$x \in L \Rightarrow \mathbb{P}\big(M(x) = 1\big) \geq \frac{1}{p(|x|)}$$
$$x \notin L \Rightarrow \mathbb{P}\big(M(x) = 0\big) = 1.$$

Definition 2. ($\mathsf{RP2}$): $L \in \mathsf{RP2}$ if there exist a polytime PTM M and a polynomial $p : \mathbb{N} \to \mathbb{N}$, where $p \geq 1$, such that for every $x \in \{0, 1\}^*$

$$x \in L \Rightarrow \mathbb{P}\big(M(x) = 1\big) \geq 1 - 2^{-p(|x|)}$$
$$x \notin L \Rightarrow \mathbb{P}\big(M(x) = 0\big) = 1.$$

Show that $\mathsf{RP1} = \mathsf{RP2}$.

3. Suppose you download a large movie from an internet server. Before watching it, you'd like to check that your downloaded file has no errors; i.e., the file on your machine is *identical* to the file on the server. You would like to do this check without much additional communication, so sending the entire file back to the server is not a good solution. Ignoring cryptographic considerations, this is essentially the problem of computing a checksum and there are standard ways to do this; e.g., CRCs.

For concreteness, say that the file is n bits long, the server has the bitvector $a = (a_1, \dots, a_n)$ and you have the bits $b = (b_1, \dots, b_n)$.

We'd like a guarantee of this sort:

- For every vectors a and b, our algorithm will flip some random coins, and for most outcomes of the coins, will detect whether or not a and b are identical.

Define polynomials $f_a(x) = \sum_{i=1}^{n} a_i x^i$ and $f_b(x) = \sum_{i=1}^{n} b_i x^i$. We will view these as polynomials over a field $\mathbb{F}_p$, where p is a prime number; in other words, think of $\mathbb{F}_p$ as the set of numbers $\{0, \dots, p-1\}$, and when we evaluate the polynomials at some point x, compute the answer modulo p. Now define $g = f_a - f_b$.

(a) (Easy with the hint) Fix a prime number, p. Give an upper bound on the probability that a uniformly chosen $x \in \mathbb{F}_p$ is a root of g. **Hint:** you may use the following **Theorem:** Let $f(x)$ be a non-zero polynomial of degree at most d in a single variable x over any field. Then f has at most d roots (i.e., f evaluates to zero on at most d elements of the field).

(b) Consider the following algorithm. You and the server agree on the prime p. The server picks $x \in \mathbb{F}_p$ uniformly at random. It sends you x and $f_a(x)$. You compute $g(x) = f_a(x) - f_b(x)$. If $g(x) = 0$ the algorithm announces "a and b are equal". If $g(x) \neq 0$ the algorithm announces "a and b are not equal".

i. (Easy with the hint) What is the computational complexity of picking the prime p, and how many bits are required to transmit x and $f_a(x)$? **Hint:** A fact known as *Bertrand's Postulate* implies that for any $n \in \mathbb{N}_+$, there always exists a prime in $[2n, 4n]$.

ii. (Easy) Is the algorithm in the previous part one-sided or two-sided error ? Explain your answer.

4. (Hard without hint; Medium with hint (requires work)) **The weakest possible BPP definition.** Show that $L \in \mathsf{BPP}$ if and only if there exist a polynomial-time computable function $f : \mathbb{N} \to [0, 1]$, a positive polynomial $p : \mathbb{N} \to \mathbb{N}$, and a polytime PTM M such that for every $x \in \{0, 1\}^*$:

$$x \in L \Rightarrow \mathbb{P}\big(M(x) = 1\big) \geq f(|x|) + \frac{1}{p(|x|)}$$
$$x \notin L \Rightarrow \mathbb{P}\big(M(x) = 1\big) < f(|x|) - \frac{1}{p(|x|)}.$$

Hint: On input x, define a new PTM, N, that invokes $M(x)$ n times for some n to be determined. Compute $\hat{p} = \frac{1}{n}\sum_{i=1}^{n} t_i$, where $t_i \in \{0, 1\}$ is the result of the ith invocation of M on x. Accept if $\hat{p} > f(|x|)$ and otherwise reject. Now apply a version of Chernoff's inequality.

5. (Easy if you solved previous problem; Medium if using hint from previous problem; otherwise Hard) **The strongest possible BPP definition.** Show that for every $L \in \mathsf{BPP}$ and every positive polynomial $p : \mathbb{N} \to \mathbb{N}$, there is polytime PTM M such that for every $x \in \{0, 1\}^*$:

$$x \in L \Rightarrow \mathbb{P}\big(M(x) = 1\big) \geq 1 - 2^{-p(|x|)}$$
$$x \notin L \Rightarrow \mathbb{P}\big(M(x) = 1\big) < 2^{-p(|x|)}.$$