Homework 8

Due Saturday, November 7

Since we haven't introduced any new algorithms this week, there will be no implementation part.

Written Part

1. In Hw 7 problem 7c you described an algorithm that recovered the first k bits of the discrete log modulo p, assuming that $p-1$ is divisible by 2^k. Prove the correctness of this algorithm. In particular, there is some ambiguity when you take the square root in last week's algorithm. Why does the assumption that $p-1$ is divisible by 2^k alleviate this ambiguity?

2. We've given several proofs of Fermat's Little Theorem. This exercise outlines another one that is of a very different flavor. Throughout we fix a prime number p.

   (a) Let j be an integer with $1 \le j \le p-1$. Prove that $\binom{j}{p}$ is divisible by p.

   (b) For any integers a, b, show that:

   $$(a+b)^p \equiv a^p + b^p \mod p.$$

   (This identity is often called the *freshman's dream* by jaded calculus professors).

   (c) Prove Fermat's Little Theorem: $a^p \equiv a \mod p$ by induction on a using part (b) with $b = 1$.

3. Suppose we flip a coin 10 times. Compute the probability of the following event.

   (a) The probability that the first and last coins are both heads.

   (b) The probability that at least one of the first and last coins is heads.

   (c) The probability that exactly 5 coin tosses are heads.

   (d) The probability that exactly k coin tosses are heads.

   (e) The probability that an even number of coin tosses are heads.

   (f) The probability that an odd number of coin tosses are heads.

4. We let $Pr : \Omega \to \mathbb{R}$ be a probability theory.

   (a) Let E be an event, and E^c its complement. Prove $Pr(E^c) = 1 - Pr(E)$.

   (b) Let E and F be disjoint events. Prove that

   $$Pr(E \cup F) = Pr(E) + Pr(F).$$

   (c) Let E and F be any two events (not necessarily disjoint). Prove that

   $$Pr(E \cup F) = Pr(E) + Pr(F) - Pr(E \cap F).$$

   (d) Let E_1, E_2, and E_3 be events. Prove that:

   $$\begin{aligned} Pr(E_1 \cup E_2 \cup E_3) = \quad & Pr(E_1) + Pr(E_2) + Pr(E_3) - Pr(E_1 \cap E_2) - Pr(E_1 \cap E_3) \\ & -Pr(E_2 \cap E_3) + Pr(E_1 \cap E_2 \cap E_3). \end{aligned}$$

(e) Let $E_1, E_2, \cdots, E_n$ be n events. We say that the events are *pariwise disjoint* if $E_i \cap E_j = \emptyset$ for all $i \neq j$. Show that if the events are pairwise disjoint then:

$$Pr(E_1 \cup E_2 \cup \cdots \cup E_n) = Pr(E_1) + Pr(E_2) + \cdots + Pr(E_n).$$

(f) Let $E_1, \cdots, E_n$ be n (not necessarily disjoint) events. Conjecture a general formula for $Pr(E_1 \cup E_2 \cup \cdots \cup E_n)$ in terms of the probability of the E_i and their various intersections. This is called the *inclusion-exclusion* principle.

5. Let E, F be events.

(a) Show that $Pr(E|E) = 1$. Explain in words why this is reasonable.

(b) Suppose that E and F are disjoint. Show that $Pr(E|F) = 0$. Explain in words why this is reasonable.

(c) Let $F_1, \cdots, F_n$ be pairwise disjoint and suppose $F_1 \cup \cdots \cup F_n = \Omega$. Prove the following decomposition formula:

$$Pr(E) = \sum_{i=1}^{n} Pr(E|F_i)Pr(F_i).$$

(d) Prove the following general version of Bayes' formula:

$$Pr(F_i|E) = \frac{Pr(E|F_i)Pr(F_i)}{\sum_{j=1}^{n} Pr(E|F_j)Pr(F_j)}.$$

6. This is the famous *Monty Hall Problem.* Ralph is on a game show, and Monty Hall gives Ralph the choice of a prize, behind one of 3 closed doors. Monty tell's Ralph that behind 2 of the doors are goats, and behind the third is a new car. Ralph chooses a door, and then Monty opens one of the remaining 2 doors revealing a goat! Monty then asks Ralph: *would you rather stick to the door you chose? Or switch to the other closed door?*

(a) If Ralph always sticks with the same closed door, what are his chances of winning a car? What about if Ralph always switches? What is Ralph's best strategy?

(b) More generally, suppose that there are N doors, M cars, and Monty hall reveals K goats after Ralphs first choice. Compute the probabilities:

$$Pr(\text{Ralph wins a car} \mid \text{Ralph sticks}),$$

$$Pr(\text{Ralph wins a car} \mid \text{Ralph switches}).$$

Which is the better strategy? (Letting $N = 1000, M = 1, K = 998$ makes the solution to part (a) seem less paradoxical).

7. In this exercise we study the probability of success of a Monte Carlo algorithm in quite a bit more generality that we considered in class. Let $\mathcal{S}$ be a set (of integers), and $\mathscr{A}$ an interesting property of elements of $\mathcal{S}$. Suppose that:

$$Pr(x \in \mathcal{S} \text{ is } \textbf{not } \mathscr{A}) = \delta.$$

Suppose that you have a Monte-Carlo algorithm that takes as input a random number r and some $m \in \mathcal{S}$ and returns `Yes` or `No` satisfying:

(1) If the algorithm returns `Yes` m is *definitely* $\mathscr{A}$.

(2) If m has A, then the property that the algorithm returns `Yes` is at least P.

(a) Express conditions (1) and (2) as conditional probabilities

(b) Suppose we run the algorithm N times on a fixed $m \in \mathcal{S}$, and the algorithm returns `No` each time. Derive a lower bound in terms of δ, P and N for the probabilit that m is *not* $\mathscr{A}$. (In class we did this for $\delta = .01$ and $P = 1/2$. Here you will have to be more careful about distinguishing P and $1 - P$.)

8. We can now compute the probability of correctness for `probablyPrime`. Recall that if n is a composite number, then 75% of integers between 2 and $n - 1$ are Miller-Rabin witnesses to the compositeness of n. You will also need the prime number theorem, which we interpret as saying the probability of an integer n being prime is approximately $\ln(n)/n$.

(a) Suppose `probablyPrime(n)` returns `True`. Compute the probability that n is prime.

(b) Suppose instead of running the Miller-Rabin test on 20 potential witnesses, `probablyPrime` runs the test on N potential witnesses. If `probablyPrime(n)` returns `True`, compute the probability that n is prime in terms of N.