

# CS 573: Algorithms, Fall 2014

## Homework 0, Practice Problems

### Practice Problems

The following problems are entirely for your benefit; similar questions will appear in every homework. Don't turn in solutions—we'll just throw them out—but feel free to ask us about practice questions during office hours and review sessions. Think of them as potential exam questions (hint, hint).

#### 1. MAD COW DISEASE

(20 PTS.)

In a land far far away (i.e., Canada), a mad cow disease was spreading among cow farms. The cow farms were, naturally, organized as a  $n \times n$  grid. The epidemic started when  $m$  contaminated cows were delivered to (some) of the farms. Once one cow in a farm has Mad Cow disease then all the cows in this farm get the disease. For a farm, if two or more of its neighboring farms have the disease then the cows in the farm would get the disease. A farm in the middle of the grid has four neighboring farms (two horizontally next to it, and two vertically next to it). We are interested in how the disease spread if we wait enough time.

- (5 PTS.) Show that if  $m = n$  then there is a scenario such that all the farms in the  $n \times n$  grid get contaminated.
- (15 PTS.) **Prove**<sup>1</sup> that if  $m \leq n - 1$  then (always) not all the farms are contaminated.

#### 2. (20 PTS.) There are $n$ balls (numbered from 1 to $n$ ) and $n$ boxes (numbered from 1 to $n$ ). We put each ball in a randomly selected box.

- (a) (4 PTS.) A box may contain more than one ball. Suppose  $X$  is the number on the box that has the smallest number among all nonempty boxes. What is the expectation of  $X$ ?
- (b) (4 PTS.) What is the expected number of bins that have exactly one ball in them? (Hint: Compute the probability of a specific bin to contain exactly one ball and then use some properties of expectation.)
- (c) (8 PTS.) We put the balls into the boxes in such a way that there is exactly one ball in each box. If the number written on a ball is the same as the number written on the box containing the ball, we say there is a match. What is the expected number of matches?
- (d) (4 PTS.) What is the probability that there are exactly  $k$  matches? ( $1 \leq k < n$ )

[Hint: If you have to appeal to “intuition” or “common sense”, your answers are probably wrong!]

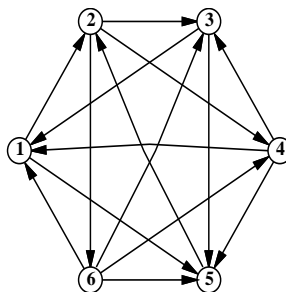
#### 3. A TRIP THROUGH THE GRAPH.

(20 PTS.)

A *tournament* is a directed graph with exactly one edge between every pair of vertices. (Think of the nodes as players in a round-robin tournament, where each edge points from the winner to the loser.) A *Hamiltonian path* is a sequence of directed edges, joined end to end, that visits every vertex exactly once. Prove that every tournament contains at least one Hamiltonian path.

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<sup>1</sup>I.e., provide a formal proof, not hand waving.



A six-vertex tournament containing the Hamiltonian path  $6 \rightarrow 4 \rightarrow 5 \rightarrow 2 \rightarrow 3 \rightarrow 1$ .

**4.** (10 PTS.)

- (a) Use induction to prove that in a simple graph, every walk between a pair of vertices,  $u, v$ , contains a path between  $u$  and  $v$ . Recall that a walk is a list of the form  $v_0, e_1, v_1, e_2, v_2, \dots, e_k, v_k$ , in which  $e_i$  has endpoints  $v_{i-1}$  and  $v_i$ .
- (b) Prove that a graph is connected if and only if for every partition of its vertices into two nonempty sets, there exists an edge that has endpoints in both sets.

**5. Rolling to victory.**

(20 PTS.)

Alice and Bob each have a fair  $n$ -sided die. Alice rolls her die once. Bob then repeatedly throws his die until he rolls a number at least as big as the number Alice rolled. Each time Bob rolls, he pays Alice \$1. (For example, if Alice rolls a 5, and Bob rolls a 4, then a 3, then a 1, then a 5, the game ends and Alice gets \$4. If Alice rolls a 1, then no matter what Bob rolls, the game will end immediately, and Alice will get \$1.)

*Exactly* how much money does Alice expect to win at this game? Prove that your answer is correct. If you have to appeal to ‘intuition’ or ‘common sense’, your answer is probably wrong!

**6.** (10 PTS.)

- (a) Let  $f_i(n)$  be a sequence of functions, such that for every  $i$ ,  $f_i(n) = o(\sqrt{n})$  (namely,  $\lim_{n \rightarrow \infty} \frac{f_i(n)}{\sqrt{n}} = 0$ ). Let  $g(n) = \sum_{i=1}^n f_i(n)$ . Prove or disprove:  $g(n) = o(n^{3/2})$ .
- (b) If  $f_1(n) = O(g_1(n))$  and  $f_2(n) = O(g_2(n))$ . Prove or disprove:
  - $f_1(n) + f_2(n) = O(g_1(n) + g_2(n))$
  - $f_1(n) * f_2(n) = O(g_1(n) * g_2(n))$
  - $f_1(n)^{f_2(n)} = O(g_1(n)^{g_2(n)})$

**7.** (10 PTS.)

Describe a data structure that supports storing temperatures. The operations on the data structure are as follows:

**Insert**( $t, d$ ) — Insert the temperature  $t$  that was measured on date  $d$ . Each temperature is a real number between  $-100$  and  $150$ . For example, **insert**(22, "1/20/03").

**Average**( $d_1, d_2$ ) report what is the average of all temperatures that were measured between date  $d_1$  and date  $d_2$ .

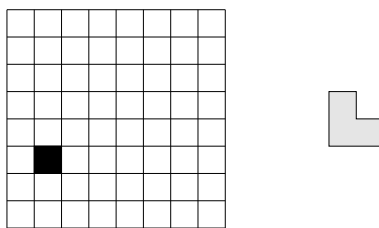
Each operation should take time  $O(\log n)$ , where  $n$  is the number of dates stored in the data structure. You can assume that a date is just an integer which specifies the number of days since the first of January 1970.

**8.** (10 PTS.)

We toss a fair coin  $n$  times. What is the expected number of “runs”? Runs are consecutive tosses with the same result. For example, the toss sequence HHHTTHTH has 5 runs.

**9.** (10 PTS.)

Consider a  $2^n \times 2^n$  chessboard with one (arbitrarily chosen) square removed, as in the following picture (for  $n = 3$ ):



Prove that any such chessboard can be tiled without gaps or overlaps by L-shapes consisting of 3 squares each.

**10.** Recall the standard recursive definition of the Fibonacci numbers:  $F_0 = 0$ ,  $F_1 = 1$ , and  $F_n = F_{n-1} + F_{n-2}$  for all  $n \geq 2$ . Prove the following identities for all positive integers  $n$  and  $m$ .

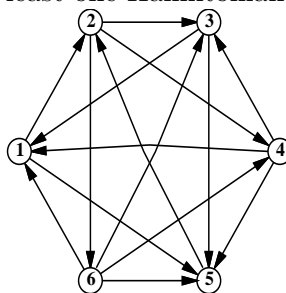
- (a)  $F_n$  is even if and only if  $n$  is divisible by 3.
- (b)  $\sum_{i=0}^n F_i = F_{n+2} - 1$
- (c)  $F_n^2 - F_{n+1}F_{n-1} = (-1)^{n+1}$
- (d) If  $n$  is an integer multiple of  $m$ , then  $F_n$  is an integer multiple of  $F_m$ .

**11.** (a) Prove the following identity by induction:

$$\binom{2n}{n} = \sum_{k=0}^n \binom{n}{k} \binom{n}{n-k}.$$

- (b) Give a non-inductive combinatorial proof of the same identity, by showing that the two sides of the equation count exactly the same thing in two different ways. There is a correct one-sentence proof.

**12.** A *tournament* is a directed graph with exactly one edge between every pair of vertices. (Think of the nodes as players in a round-robin tournament, where each edge points from the winner to the loser.) A *Hamiltonian path* is a sequence of directed edges, joined end to end, that visits every vertex exactly once. Prove that every tournament contains at least one Hamiltonian path.



A six-vertex tournament containing the Hamiltonian path  $6 \rightarrow 4 \rightarrow 5 \rightarrow 2 \rightarrow 3 \rightarrow 1$ .

**13.** Solve the following recurrences. State tight asymptotic bounds for each function in the form  $\Theta(f(n))$  for some recognizable function  $f(n)$ . You do not need to turn in proofs (in fact, please *don't* turn in proofs), but you should do them anyway just for practice. Assume reasonable but nontrivial base cases if none are supplied.

- (a)  $A(n) = A(n/2) + n$
- (b)  $B(n) = 2B(n/2) + n$
- (c)  $C(n) = n + \frac{1}{2}(C(n-1) + C(3n/4))$
- (d)  $D(n) = \max_{n/3 < k < 2n/3} (D(k) + D(n-k) + n)$
- (e)  $E(n) = 2E(n/2) + n/\lg n$  **(HARD)**
- (f)  $F(n) = \frac{F(n-1)}{F(n-2)}$ , where  $F(1) = 1$  and  $F(2) = 2$ . **(HARD)**
- (g)  $G(n) = G(n/2) + G(n/4) + G(n/6) + G(n/12) + n$  [Hint:  $\frac{1}{2} + \frac{1}{4} + \frac{1}{6} + \frac{1}{12} = 1$ .] **(HARD)**
- (h)  $H(n) = n + \sqrt{n} \cdot H(\sqrt{n})$  **(HARD)**
- (i)  $I(n) = (n-1)(I(n-1) + I(n-2))$ , where  $F(0) = F(1) = 1$  **(HARD)**
- (j)  $J(n) = 8J(n-1) - 15J(n-2) + 1$

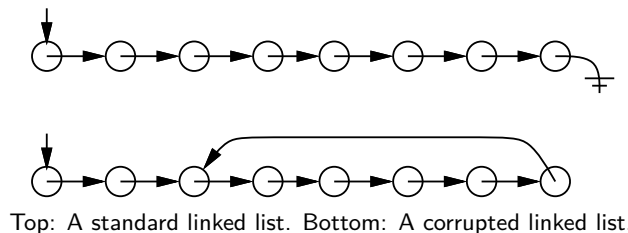
- 14.** (a) Prove that  $2^{\lceil \lg n \rceil + \lfloor \lg n \rfloor} = \Theta(n^2)$ .
- (b) Prove or disprove:  $2^{\lfloor \lg n \rfloor} = \Theta(2^{\lceil \lg n \rceil})$ .
- (c) Prove or disprove:  $2^{2^{\lfloor \lg \lg n \rfloor}} = \Theta(2^{2^{\lceil \lg \lg n \rceil}})$ .
- (d) Prove or disprove: If  $f(n) = O(g(n))$ , then  $\log(f(n)) = O(\log(g(n)))$ .
- (e) Prove or disprove: If  $f(n) = O(g(n))$ , then  $2^{f(n)} = O(2^{g(n)})$ . **(HARD)**

- (f) Prove that  $\log^k n = o(n^{1/k})$  for any positive integer  $k$ .

- 15.** This problem asks you to simplify some recursively defined boolean formulas as much as possible. In each case, prove that your answer is correct. Each proof can be just a few sentences long, but it must be a *proof*.

- (a) Suppose  $\alpha_0 = p$ ,  $\alpha_1 = q$ , and  $\alpha_n = (\alpha_{n-2} \wedge \alpha_{n-1})$  for all  $n \geq 2$ . Simplify  $\alpha_n$  as much as possible. [Hint: What is  $\alpha_5$ ?]
- (b) Suppose  $\beta_0 = p$ ,  $\beta_1 = q$ , and  $\beta_n = (\beta_{n-2} \Leftrightarrow \beta_{n-1})$  for all  $n \geq 2$ . Simplify  $\beta_n$  as much as possible. [Hint: What is  $\beta_5$ ?]
- (c) Suppose  $\gamma_0 = p$ ,  $\gamma_1 = q$ , and  $\gamma_n = (\gamma_{n-2} \Rightarrow \gamma_{n-1})$  for all  $n \geq 2$ . Simplify  $\gamma_n$  as much as possible. [Hint: What is  $\gamma_5$ ?]
- (d) Suppose  $\delta_0 = p$ ,  $\delta_1 = q$ , and  $\delta_n = (\delta_{n-2} \text{Join} \delta_{n-1})$  for all  $n \geq 2$ , where *Join* is some boolean function with two arguments. Find a boolean function *Join* such that  $\delta_n = \delta_m$  if and only if  $n-m$  is a multiple of 4. [Hint: There is only one such function.]

- 16.** Suppose you have a pointer to the head of singly linked list. Normally, each node in the list only has a pointer to the next element, and the last node's pointer is NULL. Unfortunately, your list might have been corrupted by a bug in somebody else's code<sup>2</sup>, so that the last node has a pointer back to some other node in the list instead.



<sup>2</sup>After all, *your* code is always completely 100% bug-free. Isn't that right, Mr. Gates?

Describe an algorithm that determines whether the linked list is corrupted or not. Your algorithm must not modify the list. For full credit, your algorithm should run in  $O(n)$  time, where  $n$  is the number of nodes in the list, and use  $O(1)$  extra space (not counting the list itself).

**17.** Every year, upon their arrival at Hogwarts School of Witchcraft and Wizardry, new students are sorted into one of four houses (Gryffindor, Hufflepuff, Ravenclaw, or Slytherin) by the Hogwarts Sorting Hat. The student puts the Hat on their head, and the Hat tells the student which house they will join. This year, a failed experiment by Fred and George Weasley filled almost all of Hogwarts with sticky brown goo, mere moments before the annual Sorting. As a result, the Sorting had to take place in the basement hallways, where there was so little room to move that the students had to stand in a long line.

After everyone learned what house they were in, the students tried to group together by house, but there was too little room in the hallway for more than one student to move at a time. Fortunately, the Sorting Hat took CS CS 573 many years ago, so it knew how to group the students as quickly as possible. What method did the Sorting Hat use?

- (a) More formally, you are given an array of  $n$  items, where each item has one of four possible values, possibly with a pointer to some additional data. Describe an algorithm<sup>3</sup> that rearranges the items into four clusters in  $O(n)$  time using only  $O(1)$  extra space.

<i>G</i>	<i>H</i>	<i>R</i>	<i>R</i>	<i>G</i>	<i>G</i>	<i>R</i>	<i>G</i>	<i>H</i>	<i>H</i>	<i>R</i>	<i>S</i>	<i>R</i>	<i>R</i>	<i>H</i>	<i>G</i>	<i>S</i>	<i>H</i>	<i>G</i>	<i>G</i>
Harry	Ann	Bob	Tina	Chad	Bill	Lisa	Ekta	Bart	Jim	John	Jeff	Liz	Mary	Dawn	Nick	Kim	Fox	Dana	Mel

↓

<i>G</i>	<i>G</i>	<i>G</i>	<i>G</i>	<i>G</i>	<i>G</i>	<i>G</i>	<i>H</i>	<i>H</i>	<i>H</i>	<i>H</i>	<i>H</i>	<i>R</i>	<i>R</i>	<i>R</i>	<i>R</i>	<i>R</i>	<i>R</i>	<i>S</i>	<i>S</i>
Harry	Ekta	Bill	Chad	Nick	Mel	Dana	Fox	Ann	Jim	Dawn	Bart	Lisa	Tina	John	Bob	Liz	Mary	Kim	Jeff

- (b) Describe an algorithm for the case where there are  $k$  possible values (i.e.,  $1, 2, \dots, k$ ) that rearranges the items using only  $O(\log k)$  extra space. How fast is your algorithm? (A faster algorithm would get more credit)

- (c) Describe a faster algorithm (if possible) for the case when  $O(k)$  extra space is allowed. How fast is your algorithm?

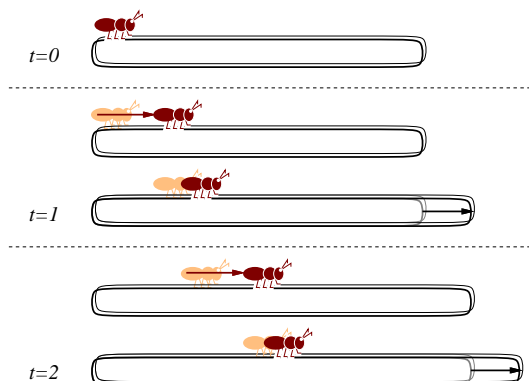
**(HARD)**

- (d) Optional practice exercise - *no credit*: Provide a fast algorithm that uses only  $O(1)$  additional space for the case where there are  $k$  possible values.

**(HARD)**

**18.** An ant is walking along a rubber band, starting at the left end. Once every second, the ant walks one inch to the right, and then you make the rubber band one inch longer by pulling on the right end. The rubber band stretches uniformly, so stretching the rubber band also pulls the ant to the right. The initial length of the rubber band is  $n$  inches, so after  $t$  seconds, the rubber band is  $n + t$  inches long.

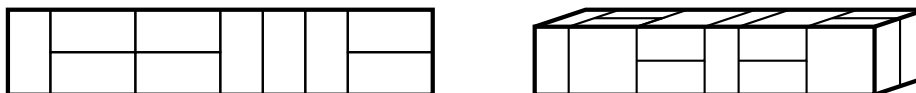
<sup>3</sup>Since you've read the Homework Instructions, you know what the phrase 'describe an algorithm' means. Right?



Every second, the ant walks an inch, and then the rubber band is stretched an inch longer.

- How far has the ant moved after  $t$  seconds, as a function of  $n$  and  $t$ ? Set up a recurrence and (for full credit) give an *exact* closed-form solution. [Hint: What *fraction* of the rubber band's length has the ant walked?]
- How long does it take the ant to get to the right end of the rubber band? For full credit, give an answer of the form  $f(n) + \Theta(1)$  for some explicit function  $f(n)$ .

- 19.** (a) A *domino* is a  $2 \times 1$  or  $1 \times 2$  rectangle. How many different ways are there to completely fill a  $2 \times n$  rectangle with  $n$  dominos? Set up a recurrence relation and give an *exact* closed-form solution.
- (b) A *slab* is a three-dimensional box with dimensions  $1 \times 2 \times 2$ ,  $2 \times 1 \times 2$ , or  $2 \times 2 \times 1$ . How many different ways are there to fill a  $2 \times 2 \times n$  box with  $n$  slabs? Set up a recurrence relation and give an *exact* closed-form solution.



A  $2 \times 10$  rectangle filled with ten dominos, and a  $2 \times 2 \times 10$  box filled with ten slabs.

- 20.** Professor George O'Jungle has a favorite 26-node binary tree, whose nodes are labeled by letters of the alphabet. The preorder and postorder sequences of nodes are as follows:

preorder: M N H C R S K W T G D X I Y A J P O E Z V B U L Q F

postorder: C W T K S G R H D N A O E P J Y Z I B Q L F U V X M

Draw Professor O'Jungle's binary tree, and give the inorder sequence of nodes.

- 21.** Alice and Bob each have a fair  $n$ -sided die. Alice rolls her die once. Bob then repeatedly throws his die until he rolls a number at least as big as the number Alice rolled. Each time Bob rolls, he pays Alice \$1. (For example, if Alice rolls a 5, and Bob rolls a 4, then a 3, then a 1, then a 5, the game ends and Alice gets \$4. If Alice rolls a 1, then no matter what Bob rolls, the game will end immediately, and Alice will get \$1.)

*Exactly* how much money does Alice expect to win at this game? Prove that your answer is correct. If you have to appeal to 'intuition' or 'common sense', your answer is probably wrong!

- 22.** Penn and Teller have a special deck of fifty-two cards, with no face cards and nothing but clubs—the ace, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, ..., 52 of clubs. (They're big cards.) Penn shuffles the deck until each of the  $52!$  possible orderings of the cards is equally likely. He then takes cards one at a time from the top of the deck and gives them to Teller, stopping as soon as he gives Teller the five of clubs.

- On average, how many cards does Penn give Teller?
- On average, what is the smallest-numbered card that Penn gives Teller? (**HARD**)

(c) On average, what is the largest-numbered card that Penn gives Teller?

[Hint: Solve for an  $n$ -card deck and then set  $n = 52$ .] In each case, give *exact* answers and prove that they are correct. If you have to appeal to “intuition” or “common sense”, your answers are probably wrong!

**23.** (10 PTS.) Evaluate the following summations; simplify your answers as much as possible. Significant partial credit will be given for answers in the form  $\Theta(f(n))$  for some recognizable function  $f(n)$ .

(a) (2 PTS.) 
$$\sum_{i=1}^n \sum_{j=1}^i \sum_{k=j}^i \frac{1}{i}$$

(HARD)

(b) (2 PTS.) 
$$\sum_{i=1}^n \sum_{j=1}^i \sum_{k=j}^i \frac{1}{j}$$

(c) (2 PTS.) 
$$\sum_{i=1}^n \sum_{j=1}^i \sum_{k=j}^i \frac{1}{k}$$

(d) (2 PTS.) 
$$\sum_{i=1}^n \sum_{j=1}^i \sum_{k=1}^j \frac{1}{k}$$

(e) (2 PTS.) 
$$\sum_{i=1}^n \sum_{j=1}^i \sum_{k=1}^j \frac{1}{j \cdot k}$$

**24.** (10 PTS.) Prove that for any nonnegative parameters  $a$  and  $b$ , the following algorithms terminate and produce identical output. Also, provide bounds on the running times of those algorithms. Can you imagine any reason why WEIRDEUCLID would be preferable to FASTEUCLID?

**SlowEuclid**( $a, b$ ) :

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if  $b > a$ 
    return SLOWEUCLID( $b, a$ )
else if  $b = 0$ 
    return  $a$ 
else
    return SLOWEUCLID( $b, a - b$ )

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**FastEuclid**( $a, b$ ) :

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if  $b = 0$ 
    return  $a$ 
else
    return FASTEUCLID( $b, a \bmod b$ )

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**WeirdEuclid**( $a, b$ ) :

```

if  $b = 0$ 
    return  $a$ 
if  $a = 0$ 
    return  $b$ 
if  $a$  is even and  $b$  is even
    return  $2 * \text{WEIRDEUCLID}(a/2, b/2)$ 
if  $a$  is even and  $b$  is odd
    return WEIRDEUCLID( $a/2, b$ )
if  $a$  is odd and  $b$  is even
    return WEIRDEUCLID( $a, b/2$ )
if  $b > a$ 
    return WEIRDEUCLID( $b - a, a$ )
else
    return WEIRDEUCLID( $a - b, b$ )

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**25.** (10 PTS.) Suppose we have a binary search tree. You perform a long sequence of operations on the binary tree (insertion, deletions, searches, etc), and the maximum depth of the tree during those operations

is at most  $h$ .

Modify the binary search tree  $T$  so that it supports the following operations. Implementing some of those operations would require you to modify the information stored in each node of the tree, and the way insertions/deletions are being handled in the tree. For each of the following, describe separately the changes made in detail, and the algorithms for answering those queries. (Note, that under the modified version of the binary search tree, insertion and deletion should still take  $O(h)$  time, where  $h$  is the maximum height of the tree during all the execution of the algorithm.)

- (a) (2 PTS.) Find the smallest element stored in  $T$  in  $O(h)$  time.
- (b) (2 PTS.) Given a query  $k$ , find the  $k$ -th smallest element stored in  $T$  in  $O(h)$  time.
- (c) (3 PTS.) Given a query  $[a, b]$ , find the number of elements stored in  $T$  with their values being in the range  $[a, b]$ , in  $O(h)$  time.
- (d) (3 PTS.) Given a query  $[a, b]$ , report (i.e., printout) all the elements stored in  $T$  in the range  $[a, b]$ , in  $O(h + u)$  time, where  $u$  is the number of elements printed out.

**26.** Given a set of points  $P$  in the plane, the convex hull of  $P$  is the smallest convex polygon that contains  $P$ . A point of  $P$  is called a corner of  $\mathcal{CH}(P)$  if it does not lie in the interior of the edges of  $\mathcal{CH}(P)$ .

- (a) Let  $V$  be a subset of the integer grid  $U = \{(i, j) \mid 1 \leq i \leq n, 1 \leq j \leq n\}$ . Prove that  $\mathcal{CH}(V)$  has at most  $O(n^{2/3})$  corners.
- (b) A point  $(a, b) \in U$  is primitive if  $\gcd(a, b) = 1$ . Prove that the number of primitive points in  $U$  is  $\Omega(n^2)$ . (Hint: consider the Euler number  $\phi(n)$ , which is the cardinality of the set of numbers smaller than  $n$  that has gcd 1 with  $n$ . Namely,  $\phi(n) = \left| \left\{ a \mid 0 \leq a < n, \gcd(a, n) = 1 \right\} \right|$ . Prove that  $\sum_{i=1}^n \phi(i)n/i = \Omega(n^2)$ .)
- (c) Show a subset  $V \subseteq U$ , such that  $\mathcal{CH}(V)$  has  $\Omega(n^{2/3})$  corners.

**27.** CORNIFICATION<sup>4</sup>

(20 PTS.)

During the sweetcorn festival in Urbana, you had been kidnapped by an extreme anti corn organization called Al Corona. To punish you, they give you several sacks with a total of  $(n + 1)n/2$  cobs of corn in them, and an infinite supply of empty sacks. Next, they ask you to play the following game: At every point in time, you take a cob from every non-empty sack, and you put this set of cobs into a new sack. The game terminates when you have  $n$  non-empty sacks, with the  $i$ th sack having  $i$  cobs in it, for  $i = 1, \dots, n$ . For example, if we started with  $\{1, 5\}$  (i.e., one sack has 1 cob, the other 5), we would have the following sequence of steps:  $\{2, 4\}$ ,  $\{1, 2, 3\}$  and the game ends.

- (a) (5 PTS.) Prove that the game terminates if you start from a configuration where all the cobs are in a single sack.
- (b) (5 PTS.) Provide a bound, as tight as possible, on the number of steps in the game till it terminates in the case where you start with a single sack.
- (c) (5 PTS.) (hard) Prove that the game terminates if you start from an arbitrary configuration where the cobs might be in several sacks.
- (d) (5 PTS.) Provide a bound, as tight as possible, on the number of steps in the game till it terminates in the general case.

**28.** RECURRENCES

(20 PTS.)

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<sup>4</sup>Cornification - Conversion into, or formation of, horn; a becoming like horn. Source: Webster's Revised Unabridged Dictionary



Solve the following recurrences. State tight asymptotic bounds for each function in the form  $\Theta(f(n))$  for some recognizable function  $f(n)$ . You do not need to turn in proofs (in fact, please *don't* turn in proofs), but you should do them anyway just for practice. Assume reasonable but nontrivial base cases if none are supplied. More exact solutions are better.

(a) (1 PTS.)  $A(n) = A(n/3 + 5 + \lfloor \log n \rfloor) + n \log \log n$

(b) (1 PTS.)  $B(n) = \min_{0 < k < n} (3 + B(k) + B(n - k)).$

(c) (1 PTS.)  $C(n) = 3C(\lceil n/2 \rceil - 5) + n/\log n$

(d) (1 PTS.)  $D(n) = \frac{n}{n-5}D(n-1) + 1$

(e) (1 PTS.)  $E(n) = E(\lfloor 3n/4 \rfloor) + 1/\sqrt{n}$

(f) (1 PTS.)  $F(n) = F(\lfloor \log^2 n \rfloor) + \log n$  (**HARD**)

(g) (1 PTS.)  $G(n) = n + 7\sqrt{n} \cdot G(\lfloor \sqrt{n} \rfloor)$

(h) (1 PTS.)  $H(n) = \log^2(H(n-1)) + 1$

(i) (1 PTS.)  $I(n) = I(\lfloor n^{1/4} \rfloor) + 1$

(j) (1 PTS.)  $J(n) = J(n - \lfloor n/\log n \rfloor) + 1$

## 29. Sorting functions

(20 PTS.)

Sort the following 25 functions from asymptotically smallest to asymptotically largest, indicating ties if there are any. You do not need to turn in proofs (in fact, please *don't* turn in proofs), but you should do them anyway just for practice.

$n^{2.5} - (n-1)^{2.5}$	$n$	$n^{1.6}$	$n^{1.4}$	$1 + \lg \lg n$
$\cos n + 2$	$\lg \lg(\lg^* n)$	$(\lg n)!$	$(\lg^* n)^{4 \lg n}$	$n^4$
$\lg^* 2^{2^{2^n}}$	$2^{\lg n}$	$\sqrt{n}^{2e-1}$	$\sum_{i=1}^n i$	$\sum_{i=1}^n \sqrt{i}$
$n^{\frac{7}{n}}$	$n^{4/(2 \lg n)}$	$11 + \lfloor \lg \lg(n) \rfloor$	$(\lg(2+n))^{\lg n}$	$\left(1 + \frac{1}{194}\right)^{15n}$
$n^{1/\lg \lg n}$	$n^{\lg \lg n}$	$\lg^{(19)} n$	$n^{1/12}$	$n(\lg n)^4$

To simplify notation, write  $f(n) \ll g(n)$  to mean  $f(n) = o(g(n))$  and  $f(n) \equiv g(n)$  to mean  $f(n) = \Theta(g(n))$ . For example, the functions  $n^2$ ,  $n$ ,  $\binom{n}{2}$ ,  $n^3$  could be sorted either as  $n \ll n^2 \equiv \binom{n}{2} \ll n^3$  or as  $n \ll \binom{n}{2} \equiv n^2 \ll n^3$ . [**Hint:** When considering two functions  $f(\cdot)$  and  $g(\cdot)$  it is sometime useful to consider the functions  $\ln f(\cdot)$  and  $\ln g(\cdot)$ .]

## 30. SORTING FUNCTIONS

(20 PTS.)

Sort the following 25 functions from asymptotically smallest to asymptotically largest, indicating ties if there are any. You do not need to turn in proofs (in fact, please *don't* turn in proofs), but you should do them anyway just for practice.

$n^{5.5} - (n-1)^{5.5}$	$n$	$n^{2.2}$	$\lg^*(n/7)$	$1 + \lg \lg n$
$\cos n + 2$	$\lg(\lg^* n)$	$\lg(n!)$	$(\lg^* n)^{\lg n}$	$n^4$
$\lg^* 2^{2^n}$	$2^{\lg^* n}$	$e^{\sqrt{n}}$	$\sum_{i=1}^n \frac{1}{i}$	$\sum_{i=1}^n \frac{1}{i^2}$
$n^{\frac{3}{(2^n)}}$	$n^{3/(2 \lg n)}$	$\lfloor \lg \lg(n!) \rfloor$	$(\lg(7+n))^{\lg n}$	$\left(1 + \frac{1}{154}\right)^{154n}$
$n^{1/\lg \lg n}$	$n^{\lg \lg n}$	$\lg^{(200)} n$	$n^{1/1234}$	$n(\lg n)^3$

To simplify notation, write  $f(n) \ll g(n)$  to mean  $f(n) = o(g(n))$  and  $f(n) \equiv g(n)$  to mean  $f(n) = \Theta(g(n))$ . For example, the functions  $n^2$ ,  $n$ ,  $\binom{n}{2}$ ,  $n^3$  could be sorted either as  $n \ll n^2 \equiv \binom{n}{2} \ll n^3$  or as  $n \ll \binom{n}{2} \equiv n^2 \ll n^3$ .

**31.** (20 PTS.) There are  $n$  balls (numbered from 1 to  $n$ ) and  $n$  boxes (numbered from 1 to  $n$ ). We put each ball in a randomly selected box.

- (a) (8 PTS.) A box may contain more than one ball. Suppose  $X$  is the number on the box that has the smallest number among all nonempty boxes. What is the expectation of  $X$ ? (It's OK to just give a big expression.)
- (b) (8 PTS.) We put the balls into the boxes in such a way that there is exactly one ball in each box. If the number written on a ball is the same as the number written on the box containing the ball, we say there is a match. What is the expected number of matches?
- (c) (4 PTS.) What is the probability that there are exactly  $k$  matches? ( $1 \leq k < n$ )

[Hint: If you have to appeal to “intuition” or “common sense”, your answers are probably wrong!]

**32.** COLORING  
(10 PTS.)

- (a) (5 PTS.) Let  $T_1, T_2$  and  $T_3$  be three trees defined over the set of vertices  $\{v_1, \dots, v_n\}$ . Prove that the graph  $G = T_1 \cup T_2 \cup T_3$  is colorable using six colors ( $e$  is an edge of  $G$  if and only if it is an edge in one of trees  $T_1, T_2$  and  $T_3$ ).
- (b) (5 PTS.) Describe an efficient algorithm for computing this coloring. What is the running time of your algorithm?

**33.** RANDOM ELECTIONS  
(10 PTS.)

You are in a shop trying to buy green tea. There  $n$  different types of green tea that you are considering:  $T_1, \dots, T_n$ . You have a coin, and you decide to randomly choose one of them using random coin flips. Because of the different prices of the different teas, you decide that you want to choose the  $i$ th tea with probability  $p_i$  (of course,  $\sum_{i=1}^n p_i = 1$ ).

Describe an algorithm that chooses a tea according to this distribution, using only coin flips. Compute the expected number of coin flips your algorithm uses. (Your algorithm should minimize the number of coin flips it uses, since if you flip coins too many times in the shop, you might be arrested.)

**34.** Graphs! Graphs!  
(20 PTS.)

A set  $S$  of vertices in an undirected connect graph  $G = (V, E)$  is *influential*, if every vertex in  $G$  is in distance at most 2 from a vertex of  $S$ . (Namely, for every vertex  $v \in V$ , there exists  $u \in V$  and  $s \in S$ , such that  $vu \in E$  and  $us \in E$ ).

- (a) (5 PTS.) *Prove or disprove* that if in a graph  $G$  the maximum degree is  $k$ , then the graph has an influential set of size  $O(n/k^2)$ , where  $n$  is the number of vertices in the graph.
- (b) (5 PTS.) *Prove or disprove* that if in a graph  $G$  the maximum degree is  $k$ , then any influential set in the graph is of size  $\Omega(n/k^2)$ .
- (c) (10 PTS.) Provide an efficient algorithm (i.e., the running time is polynomial in  $n$ ) that computes an influential set. Here the graph has minimum degree  $k$  and it is connected. How large is the influential set computed by your graph, if the minimum degree in the graph is  $k$ ? (The smaller the influential set computed by your algorithm as a function of  $n$  and  $k$ , the better. Hint: Computing the smallest influential set is unlikely to be done efficiently.)

In particular, provide an example where your algorithm outputs the smallest possible influential set.

### 35. Doubling graph. (20 PTS.) (20 PTS.)

- (A) There are  $n$  people, and  $n$  coupons. Each person randomly select 10 coupons (randomly and independently, with repetition). Consider a set  $X \subseteq \{1, \dots, n\}$  of  $k$  people, and a specific set  $Y \subseteq \{1, \dots, n\}$  of  $2k$  coupons.

Let  $\mathcal{E}(X, Y)$  be the event that all the people in  $X$  has chosen all their coupons only from  $Y$ .

Give a formula to the probability that  $\mathcal{E}(X, Y)$  happens.

- (B) Let  $\mathcal{E}_k$  be the event that any group of  $k$  people out the given set of  $n$  people, have together at most  $2k$  distinct coupons. Formally, the event of interest is  $\mathcal{E}_k = \bigcup_{\substack{X \subseteq \{1, \dots, n\} \\ |X|=k}} \bigcup_{\substack{Y \subseteq \{1, \dots, n\} \\ |Y|=2k}} \mathcal{E}(X, Y)$ .

Prove a simple (and as tight as possible) upper bound on  $\Pr[\mathcal{E}_k]$ .

(Do not use the Stirling formula, but you can use the formula  $\binom{n}{k} \leq \left(\frac{ne}{k}\right)^k$  if it helps you.)

- (C) A **doubling graph**  $G = (V, E)$  over  $n$  vertices has the property that for any subset  $S \subseteq V$ , such that  $|S| \leq n/100$  vertices, we have  $|\Gamma(S)| \geq 2k$ , where  $\Gamma(S) = \{u \mid uv \in E, v \in S\}$  is the set of all vertices adjacent to  $S$  in  $G$ .

Consider now the graph built by picking for each vertex, randomly, 10 neighbors to connect to, randomly and independently. Using (A) and (B), prove that the resulting graph is a **doubling graph** with constant probability.

- (D) Let  $G$  be the graph built in (C), and assume that it is indeed doubling. Prove that it is connected with high probability.
- (E) Prove that a doubling graph has diameter  $O(\log n)$ .

### 36. Moving numbers. (50 PTS.)

- (A) (25 PTS.) The input is a multiset  $X$  of  $n$  positive integer numbers in the range 1 to  $k$ . Consider the famous algorithm:

**Play**( $X$ ) :

```

while  $X$  contains more than one element do
    if  $X$  contains the number 0 then
        Remove the number 0 from  $X$ 
    continue
    Two distinct elements  $x_1$  and  $x_2$  are chosen arbitrarily from  $X$ 
     $y_1 = \min(x_1, x_2) - 1$ 
     $y_2 = \max(x_1, x_2) + 1$ 
     $X \leftarrow (X \setminus \{x_1, x_2\}) \cup \{y_1, y_2\}$ 
    
```

Here is an example of the execution of **Play**( $\{1, 2, 3, 4\}$ ).

$$\begin{aligned}
 \{1, 2, 3, 4\} &\Rightarrow \{1, 2, 2, 5\} \Rightarrow \{0, 2, 3, 5\} \Rightarrow \{2, 3, 5\} \Rightarrow \{2, 2, 6\} \\
 &\Rightarrow \{3, 1, 6\} \Rightarrow \{1, 2, 7\} \Rightarrow \{1, 8, 1\} \Rightarrow \{0, 2, 8\} \\
 &\Rightarrow \{2, 8\} \Rightarrow \{1, 9\} \Rightarrow \{0, 10\} \Rightarrow \{10\}.
 \end{aligned}$$

**Prove** (maybe using induction, but you do not have to) that **Play** always terminates.

(Hint: Come up with an argument why in each step some non-trivial progress is being made.)

- (B) (25 PTS.) (Harder.) Prove that the algorithm always terminates after  $O((kn)^2)$  steps.

**Extra fun questions:** Since this problem is so much “fun”, here are a few more questions. Do not submit a solution for this part (we also will not provide solutions to this part).

- (I) (Hard.) Prove that, in the worst case,  $\Theta((kn)^{3/2})$  steps are needed (that is, improve the upper bound, and provide a matching lower bound) if  $k \leq n$ . For  $k > n$ , prove that the right bound is  $\Theta(kn^2)$ .

- (II) Show that if instead of increasing the maximum number by one, we increase it by two, then the number of steps in the worst case can be exponential.
- (III) (Easy.) Consider the modified algorithm, where the algorithm repeatedly takes a subset of numbers (out of the current set of numbers), decrease the smallest number in the subset by 1, and change the value of all the other numbers in an arbitrary fashion (again, we remove a number when it becomes zero). Prove that this algorithm always terminates.

### 37. Random walk. (20 PTS.)

A **random walk** is a walk on a graph  $G$ , generated by starting from a vertex  $v_0 = v \in V(G)$ , and in the  $i$ th stage, for  $i > 0$ , randomly selecting one of the neighbors of  $v_{i-1}$  and setting  $v_i$  to be this vertex. A walk  $v_0, v_1, \dots, v_m$  is of length  $m$ .

- (A) For a vertex  $u \in V(G)$ , let  $P_u(m, v)$  be the probability that a random walk of length  $m$ , starting from  $u$ , visits  $v$  (i.e.,  $v_i = v$  for some  $i$ ).

Prove that a graph  $G$  with  $n$  vertices is connected, if and only if, for any two vertices  $u, v \in V(G)$ , we have  $P_u(n-1, v) > 0$ .

- (B) Prove that a graph  $G$  with  $n$  vertices is connected if and only if for any pair of vertices  $u, v \in V(G)$ , we have  $\lim_{m \rightarrow \infty} P_u(m, v) = 1$ .