1. A *meldable priority queue* stores a set of keys from some totally-ordered universe (such as the integers) and supports the following operations:

   - MAKEQUEUE: Return a new priority queue containing the empty set.
   - FINDMIN(Q): Return the smallest element of Q (if any).
   - DELETEMIN(Q): Remove the smallest element in Q (if any).
   - INSERT(Q, x): Insert element x into Q, if it is not already there.
   - DECREASEKEY(Q, x, y): Replace an element $x \in Q$ with a smaller key y. (If $y > x$, the operation fails.) The input is a pointer directly to the node in Q containing x.
   - DELETE(Q, x): Delete the element $x \in Q$. The input is a pointer directly to the node in Q containing x.
   - MELD(Q_1, Q_2): Return a new priority queue containing all the elements of Q_1 and Q_2; this operation destroys Q_1 and Q_2.

   A simple way to implement such a data structure is to use a ***heap-ordered binary tree*** — each node stores a priority, which is smaller than the priorities of its children, along with pointers to its parent and at most two children. MELD can be implemented using the following randomized algorithm:

```
MELD(Q1, Q2):
  if Q1 is empty return Q2
  if Q2 is empty return Q1
  if priority(Q1) > priority(Q2)
      swap Q1 ↔ Q2
  with probability 1/2
      left(Q1) ← MELD(left(Q1), Q2)
  else
      right(Q1) ← MELD(right(Q1), Q2)
  return Q1
```

   (a) Prove that for *any* heap-ordered binary trees Q_1 and Q_2 (***not*** just those constructed by the operations listed above), the expected running time of MELD(Q_1, Q_2) is $O(\log n)$, where $n = |Q_1| + |Q_2|$. *[Hint: How long is a random root-to-leaf path in an n-node binary tree if each left/right choice is made uniformly and independently at random?]*

   (b) Show that each of the other meldable priority queue operations can be implemented with at most one call to MELD and $O(1)$ additional time. (This implies that every operation takes $O(\log n)$ expected time.)

2. Recall that a *priority search tree* is a binary tree in which every node has both a *search key* and a *priority*, arranged so that the tree is simultaneously a binary search tree for the keys and a min-heap for the priorities. A *treap* is a priority search tree whose search keys are given by the user and whose priorities are independent random numbers.

   A ***heater*** is a priority search tree whose *priorities* are given by the user and whose *search keys* are distributed uniformly and independently at random in the real interval $[0, 1]$. Intuitively, a heater is a sort of anti-treap.[1]

[1]There are those who think that life has nothing left to chance, a host of holy horrors to direct our aimless dance.

The following problems consider an n-node heater T. We identify nodes in T by their *priority rank*; for example, "node 5" means the node in T with the 5th smallest priority. The min-heap property implies that node 1 is the root of T. You may assume all search keys and priorities are distinct. Finally, let i and j be arbitrary integers with $1 \le i < j \le n$.

(a) Prove that if we permute the set $\{1, 2, \dots, n\}$ uniformly at random, integers i and j are adjacent with probability $2/n$.

(b) Prove that node i is an ancestor of node j with probability $2/(i+1)$. *[Hint: Use part (a)!]*

(c) What is the probability that node i is a *descendant* of node j? *[Hint: Don't use part (a)!]*

(d) What is the *exact* expected depth of node j?

(e) Describe and analyze an algorithm to insert a new item into an n-node heater.

(f) Describe and analyze an algorithm to delete the smallest priority (the root) from an n-node heater.

*3. ***Extra credit; due October 15.*** In the usual theoretical presentation of treaps, the priorities are random real numbers chosen uniformly from the interval $[0, 1]$. In practice, however, computers have access only to random *bits*. This problem asks you to analyze an implementation of treaps that takes this limitation into account.

Suppose the priority of a node v is abstractly represented as an infinite sequence $\pi_v[1..\infty]$ of random bits, which is interpreted as the rational number

$$priority(v) = \sum_{i=1}^{\infty} \pi_v[i] \cdot 2^{-i}.$$

However, only a finite number ℓ_v of these bits are actually known at any given time. When a node v is first created, *none* of the priority bits are known: $\ell_v = 0$. We generate (or "reveal") new random bits only when they are necessary to compare priorities. The following algorithm compares the priorities of any two nodes in $O(1)$ expected time:

```
LARGERPRIORITY(v, w):
  for i ← 1 to ∞
      if i > ℓ_v
          ℓ_v ← i;  π_v[i] ← RANDOMBIT
      if i > ℓ_w
          ℓ_w ← i;  π_w[i] ← RANDOMBIT
      if π_v[i] > π_w[i]
          return v
      else if π_v[i] < π_w[i]
          return w
```

Suppose we insert n items one at a time into an initially empty treap. Let $L = \sum_v \ell_v$ denote the total number of random bits generated by calls to LARGERPRIORITY during these insertions.

(a) Prove that $E[L] = \Theta(n)$.

(b) Prove that $E[\ell_v] = \Theta(1)$ for any node v. *[Hint: This is equivalent to part (a). Why?]*

(c) Prove that $E[\ell_{\text{root}}] = \Theta(\log n)$. *[Hint: Why doesn't this contradict part (b)?]*

CS 473 Fall 2013 — Homework 4 Problem 1

Name:	NetID:
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Section: T4 T5 W2 W3 W5 None	

(a) Prove that for *any* heap-ordered binary trees Q_1 and Q_2, the expected running time of $\textsc{Meld}(Q_1, Q_2)$ is $O(\log n)$, where $n = |Q_1| + |Q_2|$.

(b) Show that each of the other meldable priority queue operations can be implemented with at most one call to $\textsc{Meld}$ and $O(1)$ additional time.

CS 473 Fall 2013 — Homework 4 Problem 2

Name:	NetID:
Name:	NetID:
Name:	NetID:
Section: T4 T5 W2 W3 W5 None	

(a) Prove that if we permute the set $\{1, 2, \ldots, n\}$ uniformly at random, integers i and j are adjacent with probability $2/n$.

(b) Prove that in any heater, node i is an ancestor of node j with probability $2/(i+1)$.

(c) What is the probability that node i is a *descendant* of node j?

(d) What is the *exact* expected depth of node j?

(e) Describe and analyze an algorithm to insert a new item into a heater.

(f) Describe and analyze an algorithm to delete the smallest priority (the root) from a heater.

CS 473 Fall 2013 — Homework 4 Problem 3

Extra credit — due October 15

Name:	NetID:
Name:	NetID:
Name:	NetID:
Section: T4 T5 W2 W3 W5 None	

Suppose we insert n items one at a time into an initially empty treap. Let $L = \sum_v \ell_v$ denote the total number of random bits generated by calls to LargerPriority during these insertions.

(a) Prove that $E[L] = \Theta(n)$.

(b) Prove that $E[\ell_v] = \Theta(1)$ for any node v.

(c) Prove that $E[\ell_{\text{root}}] = \Theta(\log n)$.
