Programming Assignment 1: Percolation

Write a program to estimate the value of the *percolation threshold* via Monte Carlo simulation.

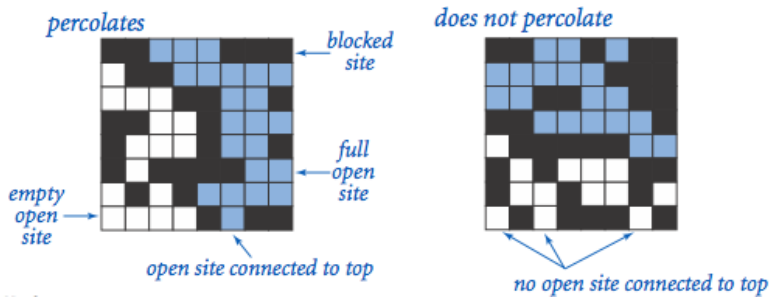
Install a Java programming environment. Install a Java programming environment on your computer by following these step-by-step instructions for your operating system [Mac OS X · Windows · Linux]. After following these instructions, the commands `javac-algs4` and `java-algs4` will classpath in algs4.jar, which contains Java classes for I/O and all of the algorithms in the textbook.

Note that, as of August 2015, you must use the named package version of `algs.jar`. To access a class, you need an import statement, such as the ones below:

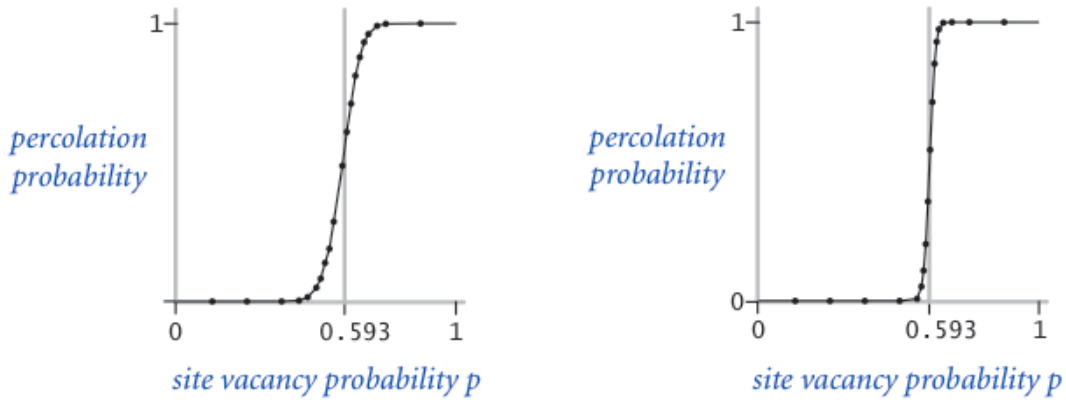
```
import edu.princeton.cs.algs4.StdRandom;
import edu.princeton.cs.algs4.StdStats;
import edu.princeton.cs.algs4.WeightedQuickUnionUF;
```

Percolation. Given a composite systems comprised of randomly distributed insulating and metallic materials: what fraction of the materials need to be metallic so that the composite system is an electrical conductor? Given a porous landscape with water on the surface (or oil below), under what conditions will the water be able to drain through to the bottom (or the oil to gush through to the surface)? Scientists have defined an abstract process known as *percolation* to model such situations.

The model. We model a percolation system using an *N*-by-*N* grid of *sites*. Each site is either *open* or *blocked*. A *full* site is an open site that can be connected to an open site in the top row via a chain of neighboring (left, right, up, down) open sites. We say the system *percolates* if there is a full site in the bottom row. In other words, a system percolates if we fill all open sites connected to the top row and that process fills some open site on the bottom row. (For the insulating/metallic materials example, the open sites correspond to metallic materials, so that a system that percolates has a metallic path from top to bottom, with full sites conducting. For the porous substance example, the open sites correspond to empty space through which water might flow, so that a system that percolates lets water fill open sites, flowing from top to bottom.)



The problem. In a famous scientific problem, researchers are interested in the following question: if sites are independently set to be open with probability p (and therefore blocked with probability $1 - p$), what is the probability that the system percolates? When p equals 0, the system does not percolate; when p equals 1, the system percolates. The plots below show the site vacancy probability p versus the percolation probability for 20-by-20 random grid (left) and 100-by-100 random grid (right).



When N is sufficiently large, there is a *threshold* value p^* such that when $p < p^*$ a random N-by-N grid almost never percolates, and when $p > p^*$, a random N-by-N grid almost always percolates. No mathematical solution for determining the percolation threshold p^* has yet been derived. Your task is to write a computer program to estimate p^*.

Percolation data type. To model a percolation system, create a data type `Percolation` with the following API:

```
public class Percolation {
   public Percolation(int N)                // create N-by-N grid, with all
sites blocked
   public void open(int i, int j)           // open site (row i, column j) if
it is not open already
   public boolean isOpen(int i, int j)      // is site (row i, column j) open?
   public boolean isFull(int i, int j)      // is site (row i, column j) full?
   public boolean percolates()              // does the system percolate?

   public static void main(String[] args)   // test client (optional)
}
```

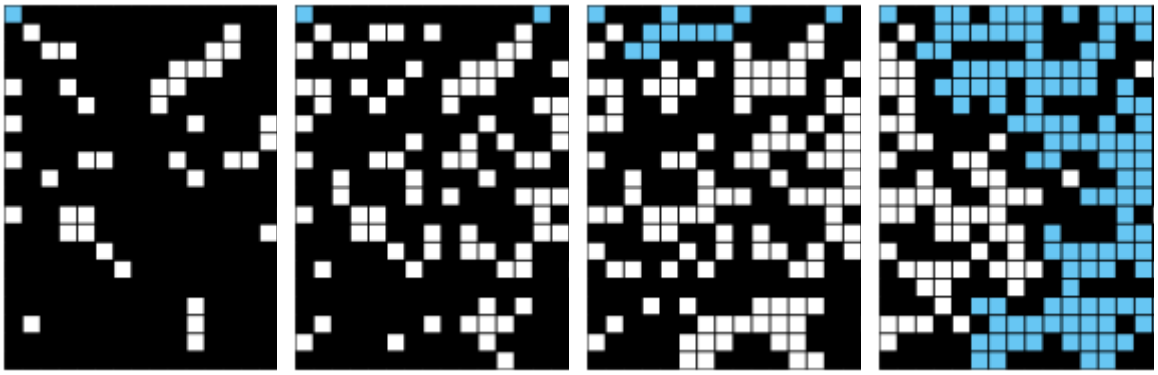
Corner cases. By convention, the row and column indices i and j are integers between 1 and N, where (1, 1) is the upper-left site: Throw a `java.lang.IndexOutOfBoundsException` if any argument to `open()`,`isOpen()`, or `isFull()` is outside its prescribed range. The constructor should throw a `java.lang.IllegalArgumentException` if $N \leq 0$.

Performance requirements. The constructor should take time proportional to N^2; all methods should take constant time plus a constant number of calls to the union-find methods `union()`, `find()`, `connected()`, and `count()`.

Monte Carlo simulation. To estimate the percolation threshold, consider the following computational experiment:

- Initialize all sites to be blocked.
- Repeat the following until the system percolates:
  - Choose a site (row *i*, column *j*) uniformly at random among all blocked sites.
  - Open the site (row *i*, column *j*).
- The fraction of sites that are opened when the system percolates provides an estimate of the percolation threshold.

For example, if sites are opened in a 20-by-20 lattice according to the snapshots below, then our estimate of the percolation threshold is 204/400 = 0.51 because the system percolates when the 204th site is opened.



50 open sites *100 open sites* *150 open sites* *204 open sites*

By repeating this computation experiment T times and averaging the results, we obtain a more accurate estimate of the percolation threshold. Let x_t be the fraction of open sites in computational experiment t. The sample mean μ provides an estimate of the percolation threshold; the sample standard deviation σ measures the sharpness of the threshold.

$$\mu = \frac{x_1 + x_2 + \cdots + x_T}{T}, \quad \sigma^2 = \frac{(x_1 - \mu)^2 + (x_2 - \mu)^2 + \cdots + (x_T - \mu)^2}{T - 1}$$

Assuming T is sufficiently large (say, at least 30), the following provides a 95% confidence interval for the percolation threshold:

$$\left[\mu - \frac{1.96\sigma}{\sqrt{T}}, \ \mu + \frac{1.96\sigma}{\sqrt{T}} \right]$$

To perform a series of computational experiments, create a data type `PercolationStats` with the following API.

```
public class PercolationStats {
   public PercolationStats(int N, int T)        // perform T independent
experiments on an N-by-N grid
   public double mean()                          // sample mean of percolation
threshold
   public double stddev()                        // sample standard deviation of
percolation threshold
   public double confidenceLo()                  // low  endpoint of 95%
confidence interval
   public double confidenceHi()                  // high endpoint of 95%
confidence interval

   public static void main(String[] args)    // test client (described below)
}
```

The constructor should throw a `java.lang.IllegalArgumentException` if either $N \leq 0$ or $T \leq 0$.

Also, include a `main()` method that takes two *command-line arguments* N and T, performs T independent computational experiments (discussed above) on an N-by-N grid, and prints the mean, standard deviation, and the *95% confidence interval* for the percolation threshold. Use `StdRandom` to generate random numbers; use `StdStats` to compute the sample mean and standard deviation.

```
% java PercolationStats 200 100
mean                    = 0.5929934999999997
stddev                  = 0.00876990421552567
95% confidence interval = 0.5912745987737567, 0.5947124012262428

% java PercolationStats 200 100
mean                    = 0.592877
stddev                  = 0.009990523717073799
95% confidence interval = 0.5909188573514536, 0.5948351426485464


% java PercolationStats 2 10000
mean                    = 0.666925
stddev                  = 0.11776536521033558
95% confidence interval = 0.6646167988418774, 0.6692332011581226

% java PercolationStats 2 100000
mean                    = 0.6669475
stddev                  = 0.11775205263262094
95% confidence interval = 0.666217665216461, 0.6676773347835391
```

Analysis of running time and memory usage (optional and not graded). Implement the `Percolation` data type using the *quick find* algorithm in `QuickFindUF`.

- Use `Stopwatch` to measure the total running time of `PercolationStats` for various values of `N` and `T`. How does doubling N affect the total running time? How does doubling T affect the total running time? Give a formula (using

tilde notation) of the total running time on your computer (in seconds) as a single function of both *N* and *T*.

- Using the 64-bit memory-cost model from lecture, give the total memory usage in bytes (using tilde notation) that a `Percolation` object uses to model an *N*-by-*N* percolation system. Count all memory that is used, including memory for the union-find data structure.

Now, implement the `Percolation` data type using the *weighted quick union* algorithm in `WeightedQuickUnionUF`. Answer the questions in the previous paragraph.

Deliverables. Submit only `Percolation.java` (using the weighted quick-union algorithm from `WeightedQuickUnionUF`) and `PercolationStats.java`. We will supply `algs4.jar`. Your submission may not call library functions except those in `StdIn`, `StdOut`, `StdRandom`, `StdStats`, `WeightedQuickUnionUF`, and `java.lang`.

For fun. Create your own percolation input file and share it in the discussion forums. For some inspiration, see these nonogram puzzles.

Programming Assignment 1 Checklist: Percolation

Frequently Asked Questions (General)

What's a checklist? The assignment provides the programming assignment specification; the checklist provides clarifications, test data, and hints that might be helpful in completing the assignment.

Which Java programming environment should I use? For novices, we recommend the lightweight IDE DrJava along with the command line. If you use our Mac OS X or Windows installer, then everything should be configured and ready to go. If you prefer to use a different IDE (such as Eclipse), that's perfectly fine too—just be sure that you know how to do the following:

- Add `algs4.jar` to your Java classpath.
- Enter command-line arguments.
- Use standard input and standard output (and, ideally, redirect them to or from a file).

Where can I find the Java code and Javadoc for the algorithms and data structures from lecture and the textbook? They are in `algs4.jar`. Here are the APIs.

Where can I find the Javadoc for the input and output libraries from lecture and the textbook? They are in `algs4.jar`. Here are the APIs.

How can I classpath in the textbook libraries from the command line? If you use our Mac OS X or Windows installer, then you can automatically classpath in the textbook libraries using the commands `javac-algs4`and `java-algs4` (instead of `javac` and `java`).

I haven't programmed in Java in a while. What material do I need to remember? For a review of our Java programming model (including our input and output libraries), read Sections 1.1 and 1.2 of *Algorithms, 4th Edition*.

Can I use various Java libraries in this assignment, such as `java.util.LinkedList`, `java.util.ArrayList`, `java.util.TreeMap`, and `java.util.HashMap`? No. You should not use any Java libraries until we have implemented equivalent versions in lecture. Once we have introduced them in lecture, you are free to use either the Java library version or our equivalent. You are

welcome to use classes in the Java language such as `Math.sqrt()` and `Integer.parseInt()`.

How do I throw a java.lang.IndexOutOfBoundsException? Use a `throw` statement like the following:

```
if (i <= 0 || i > N) throw new IndexOutOfBoundsException("row index i out of bounds");
```

Your code should not attempt to catch any exceptions—this will interfere with our grading scripts.

How should I format and comment my code? Here are some recommended style guidelines. Below are some that are particularly important (though we will not deduct for style in this course).

- Include a bold (or Javadoc) comment at the beginning of each file with your name, date, the purpose of the program, and how to execute it.
- Include a bold (or Javadoc) comment describing every method.
- Include a comment describing every instance variable.
- Indent consistently, using 3 or 4 spaces for each indentation level. Do not use hard tabs.
- Do not exceed 80 characters per line. This rule also applies to the `readme.txt` file.
- Avoid unexplained magic numbers, especially ones that are used more than once.

Frequently Asked Questions (Percolation)

What are the goals of this assignment?

- Set up a Java programming environment.
- Use our input and output libraries.
- Learn about a scientific application of the union–find data structure.
- Measure the running time of a program and use the doubling hypothesis to make predictions.
- Measure the amount of memory used by a data structure.

Can I add (or remove) methods to (or from) Percolation? No. You must implement the `Percolation` API exactly as specified, with the identical set of public methods and signatures or your assignment will not be graded. However, you are encouraged to add private methods that enhance the readability, maintainability, and modularity of your program. The one exception is `main()`—you are always permitted to add this method to test your code, but we will not call it unless we specify it in our API.

Can my Percolation data type assume the row and column indices are between 0 and N−1? No. The API specifies that valid row and column indices are between 1 and *N*.

Why is it so important to implement the prescribed API? Writing to an API is an important skill to master because it is an essential component of modular programming, whether you are developing software by yourself or as part of a group. When you develop a module that properly implements an API, anyone using that module (including yourself, perhaps at some later time) does not need to revisit the details of the code for that module when using it. This approach greatly simplifies writing large programs, developing software as part of a group, or developing software for use by others.

Most important, when you properly implement an API, others can write software to use your module or to test it. We do this regularly when grading your programs. For example, your `PercolationStats` client should work with our `Percolation` data type and vice versa. If you add an extra public method to `Percolation` and call them from `PercolationStats`, then your client won't work with our `Percolation` data type. Conversely, our `PercolationStats` client may not work with your `Percolation` data type if you remove a public method.

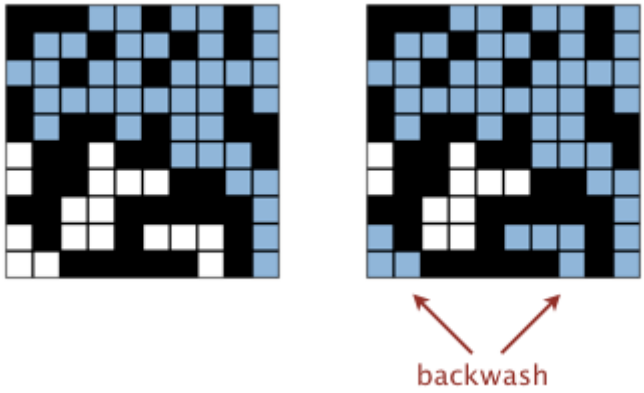
How many lines of code should my program be? You should strive for clarity and efficiency. Our reference solution for `Percolation.java` is about 70 lines, plus a test client. Our `PercolationStats.java` client is about 50 lines. If you are re-implementing the union-find data structure (instead of reusing the implementations provided), you are on the wrong track.

What assumptions can I make about the input to main() in PercolationStats? It can be any valid input: an integer $N \geq 1$ and an integer $T \geq 1$. In general, in this course you can assume that the input is of the specified format. But you do need to deal with pathological cases such as $N = 1$.

What should `stddev()` return if *T* equals 1? The sample standard deviation is undefined. We recommend returning `Double.NaN`.

After the system has percolated, my PercolationVisualizer colors in light blue all sites connected to open sites on the bottom (in addition to those connected to open sites on the top). Is this "backwash" acceptable? No, this is likely a bug in `Percolation`. It is only a minor deduction (because it impacts only the visualizer and not the experiment to estimate the percolation threshold), so don't go crazy trying to get this detail. However, many students consider this to be the most challenging and creative part of the assignment (especially if you limit yourself to one union-find object).

```
% java PercolationVisualizer input10.txt
```



How do I generate a site uniformly at random among all blocked sites for use in PercolationStats? Pick a site at random (by using `StdRandom` to generate two integers between 1 and *N*) and use this site if it is blocked; if not, repeat.

I don't get reliable timing information in PercolationStats when *N* = 200. What should I do? Increase the size of *N* (say to 400, 800, and 1600), until the mean running time exceeds its standard deviation.

Style and Bug Checkers

Style checker. We recommend using Checkstyle 6.9 (and the configuration file checkstyle.xml) to check the style of your Java programs. Here is a list of available Checkstyle checks.

Bug checker. We recommend using FindBugs 2.0.3 (and the configuration file findbugs.xml) to identify common bug patterns in your code. Here is a summary of FindBugs Bug descriptions.

Mac OS X and Windows installer. If you used our Mac OS X or Windows installer, these programs are already installed as command-line utilities. You can check a single file or multiple files via the commands:

```
% checkstyle-algs4 HelloWorld.java
% checkstyle-algs4 *.java

% findbugs-algs4 HelloWorld.class
% findbugs-algs4 *.class
```

Note that Checkstyle inspects the source code; Findbugs inspects the compiled code.

Eclipse. For Eclipse users, there is a Checkstyle plugin for Eclipse and a Findbugs plugin for Eclipse.

Caveat. The appearance of a warning message does not necessarily lead to a deduction (and, in some cases, it does not even indicate an error).

Testing

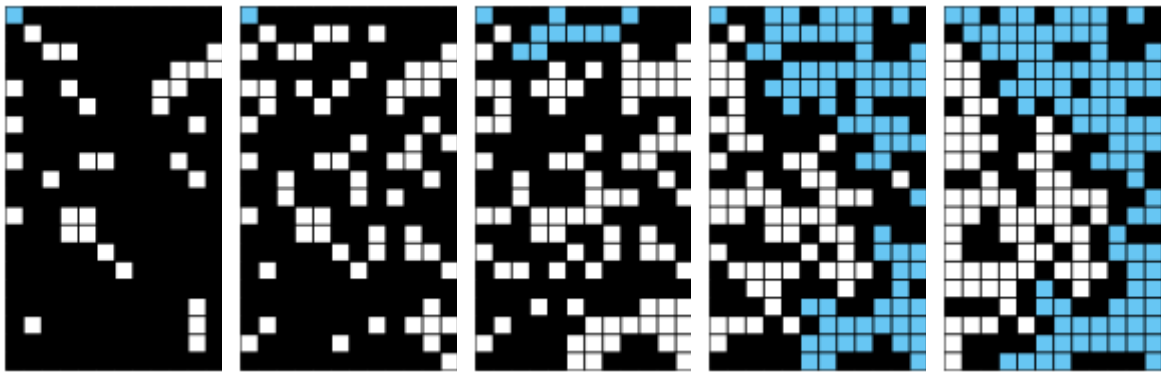
Testing. We provide two clients that serve as large-scale visual traces. We highly recommend using them for testing and debugging your `Percolation` implementation.

Visualization client. PercolationVisualizer.java animates the results of opening sites in a percolation system specified by a file by performing the following steps:

- Read the grid size *N* from the file.
- Create an *N*-by-*N* grid of sites (initially all blocked).
- Read in a sequence of sites (row *i*, column *j*) to open from the file. After each site is opened, draw full sites in light blue, open sites (that aren't full) in white, and blocked sites in black using *standard draw*, with with site (1, 1) in the upper left-hand corner.

The program should behave as in this movie and the following snapshots when used with input20.txt.

```
% java PercolationVisualizer input20.txt
```



50 open sites *100 open sites* *150 open sites* *204 open sites* *250 open sites*

Sample data files. The directory percolation contains some sample files for use with the visualization client. Associated with each input `.txt` file is an output `.png` file that contains the desired graphical output at the end of the animation. For convenience, percolation-testing.zip contains all of these files bundled together.

InteractiveVisualization client. InteractivePercolationVisualizer.java is similar to the first test client except that the input comes from a mouse (instead of from a file). It takes a command-line integer *N* that specifies the lattice size. As a bonus, it writes

to standard output the sequence of sites opened in the same format used by `PercolationVisualizer`, so you can use it to prepare interesting files for testing. If you design an interesting data file, feel free to share it with us and your classmates by posting it in the discussion forums.

Possible Progress Steps

These are purely suggestions for how you might make progress. You do not have to follow these steps.

1. **Consider not worrying about backwash for your first attempt.** If you're feeling overwhelmed, don't worry about backwash when following the possible progress steps below. You can revise your implementation once you have a better handle on the problem and have solved the problem without handling backwash.
2. **For each method in `Percolation` that you must implement (`open()`, `percolates()`, etc.), make a list of which `WeightedQuickUnionUF` methods might be useful for implementing that method.** This should help solidify what you're attempting to accomplish.
3. **Using the list of methods above as a guide, choose instance variables that you'll need to solve the problem.** Don't overthink this, you can always change them later. Instead, use your list of instance variables to guide your thinking as you follow the steps below, and make changes to your instance variables as you go. Hint: At minimum, you'll need to store the grid size, which sites are open, and which sites are connected to which other sites. The last of these is exactly what the union-find data structure is designed for.
4. **Plan how you're going to map from a 2-dimensional (row, column) pair to a 1-dimensional union find object index.** You will need to come up with a scheme for uniquely mapping 2D coordinates to 1D coordinates. We recommend writing a private method with a signature along the lines of `int xyTo1D(int, int)` that performs this conversion. You will need to utilize the percolation grid size when writing this method. Writing such a private method (instead of copying and pasting a conversion formula multiple times throughout your code) will greatly improve the readability and maintainability of your code. In general, we encourage you to write such modules wherever possible. Directly test this method using the main() function of Percolation.
5. **Write a private method for validating indices.** Since each method is supposed to throw an exception for invalid indices, you should write a private method which performs this validation process.

6. **Write the `open()` method and the `Percolation()` constructor.** The open() method should do three things. First, it should validate the indices of the site that it receives. Second, it should somehow mark the site as open. Third, it should perform some sequence of `WeightedQuickUnionUF` operations that links the site in question to its open neighbors. The constructor and instance variables should facilitate the `open()` method's ability to do its job.
7. **Test the `open()` method and the `Percolation()` constructor.** These tests should be in `main()`. An example of a simple test is to call `open(1, 1)` and `open(1, 2)`, and then to ensure that the two corresponding entries are connected (using `.connected()` in `WeightedQuickUnionUF`).
8. **Write the `percolates()`, `isOpen()`, and `isFull()` methods.** These should be very simple methods.
9. **Test your complete implementation using the visualization clients.**
10. **Write and test the PercolationStats class.**

Programming Tricks and Common Pitfalls

1. **Do not write your own union–find data structure. Use `WeightedQuickUnionUF` instead.**
2. **Your `Percolation` class must use `WeightedQuickUnionUF`.** Otherwise, it will fail the timing tests, as the autograder intercepts and counts calls to methods in `WeightedQuickUnionUF`.
3. **It's OK to use an extra row and/or column to deal with the 1-based indexing of the percolation grid.** Though it is slightly inefficient, it's fine to use arrays or union-find objects that are slightly larger than strictly necessary. Doing this results in cleaner code at the cost of slightly greater memory usage.
4. **Each of the methods (except the constructor) in `Percolation` must use a constant number of union-find operations.** If you have a for-loop inside of one of your `Percolation` methods, you're probably doing it wrong. Don't forget about the virtual-top / virtual-bottom trick described in lecture.