Homework 1—Thursday, January 14
Due Thursday, January 21, 10:30 AM

7 Required Problems (85 points), and Style and Tests (15 points)
DO NOT modify methods or method headers that were already provided to you.
DO NOT add public or protected methods.
DO introduce helper methods that are package-private (i.e. do not have a privacy modifier) as you deem necessary.

Logistics

You will notice that all of the stub files for this homework belong to the edu.upenn.cis121.hw1 package.

DO NOT change this, and be sure that any classes or test files that you create are also in this package.

You have unlimited submissions for this homework. Upon submission, our infrastructure will compile your code and run some basic test cases against the interface. These are here to test that your code compiles (i.e. you didn’t forget to add a class etc.) when we run real tests. They should not be used to test your own code’s correctness since the functionality they test is very very basic.

The compilation tests will be worth 1 point of the final score.

Also, please make sure you have Java 8 installed. Many of the projects this semester may require Java 8 for some parts of the provided code and there are some neat functional programming additions to Java for those of you coming from CIS120. It’s nice to have it set up during the 1st assignment instead of later.

You can install Java 8 by following this link and selecting the correct version for your system. If you are using Eclipse then you need to make sure that you are using the latest version, which is Eclipse Mars. If you’re on an old version, then you can follow this link to get it.

This should be enough to set you up with Java 8, but sometimes things can get messed up if you have more than one version of the JDK. Follow the more detailed instructions from this link to ensure that your Eclipse installation is set up to use Java 8.
Motivation—Image Compression

Since the dawn of time, mankind has sought to make things smaller...

Erlich Bachman

Today’s computers are constantly communicating over the network, transmitting both raw application information and user created data in the form of large files. We are already familiar with the notion that faster programs are better. This also holds true over the network; high-latency networks affect everything from multiplayer video games to standard Internet access to mission- and life-critical applications.

Faster network access is always better. However, we cannot always make an Internet link faster (the networked equivalent of throwing more hardware at the problem). Therefore, we must use intelligent algorithms to reduce our load on the network. Some of these are built directly into the internals of our computers, like TCP congestion control\(^1\) (less is more, sometimes). Others are optionally implemented at the application level, such as compression algorithms.

The goal of a lossless compression algorithm is to represent existing data through a succinct model in a way such that the original can be recovered. For example, common image compression algorithms make use of methods like segmenting the image into areas, inferring colors from adjacent pixels, or building shorter color representations based on color frequency to achieve a smaller file size that can be recovered into the original image.

In this assignment, you will implement a relatively simple lossless image compression algorithm based on quadtrees to decompose the image. You will generalize your knowledge of recursing on binary search trees to quadtrees, adapting known algorithms to perform various operations on the quadtree representation of a compressed image.

Overview

The simplest way to represent an image is to have a structure that maps every pixel in the image to a color. This is commonly known as a ‘bitmap image’. However, for large images this quickly becomes very inefficient. Take the example of a document scanned at a high resolution: Most of the page would be white pixels, and clumps of text would be black and grey pixels. Recording each white pixel of the page separately is very wasteful compared to telling the computer some region of an image should be white.

One solution is to extend this uniform region representation recursively. Instead of defining an image as a collection of arbitrary regions, we define an image as a collection of chunks. Each chunk, in turn, can either be a single color region (blank area) or collection of some other chunks. The end result of this is, of course, a tree like structure, where the entire image is represented by the root chunk and any internal nodes represent chunks that were subdivided. In this model, leaf nodes would represent uniform areas of color.

\(^1\)http://en.wikipedia.org/wiki/TCP_congestion-avoidance_algorithm
In general, splitting up chunks is not a very easy task since images come in all sorts of dimensions. We will make the following simplifications and clarifications for this assignment:

- We will only consider square images. Moreover, images will always have row and column sizes that are non-negative powers of 2; that way they can always be divided into four quadrants of equal size (excluding the case of a 1x1 region).

- A region will be considered uniform only if every pixel in it has the exact same color. As such, our compression will be lossless, meaning you will be able to exactly decompress the original image.

- Since we are recursively splitting our image into four quadrants of equal size, this kind of tree is called a quadtree. You should use the supplied enum QuadNode.QuadName to refer to each of the four quadrants (upper left, upper right, lower left, lower right).

To recap, we have defined a quadtree structure with leaves and non-leaves. Leaves are defined to be nodes with no children and a color. Non-leaves have four child nodes and no notion of a color. Notice that this definition of a quadtree guarantees a full tree; leaves have zero children, and parents have four children.

Now, how do we represent color? The Java BufferedImage class, which we look to for inspiration, stores RGB values as a single combined integer. We use that representation here. You don’t have to worry about how to generate that representation, but just know this is the reason why colors are represented as integers in this assignment. Note that 0 is a valid color in this representation.

**Part Zero: Read and understand the requirements**

Files to submit: None

Understanding the problem is the first step to solving it. Take time to read through this writeup and the Javadocs for the provided interfaces completely before starting. Get familiar with Java syntax and style conventions outlined in the course website. Go over the requirements and expectations of each class in your head and plan things out.

**Part One: Nodes and Trees (13 points)**

Files to submit: QuadNodeImpl.java, QuadNodeImplTest.java

Implement the interface defined in QuadNode.java with your own concrete implementation called QuadNodeImpl. The QuadNode interface defines the fields and methods that a single node in the tree should have, namely:

```java
public interface QuadNode {
    int getColor();
    QuadNode getQuadrant(QuadName quadrant);
}
```
Figure 1: Examples of binary images and their quad trees.
boolean isLeaf();
int getDimension();
int getSize();
void setColor(int color);
void setQuadrant(QuadName quadrant, QuadNode value);
}

Please refer to the Javadoc comments for these methods for their specifications. Keep in mind that your implementation of QuadNode should play nicely with other potential implementations of QuadNode. For example, it must accept any generic QuadNode implementation for setQuadrant.

Consider how you would go about building a compressed tree representation of an image using your own QuadNode instances. Think about how the quadtree model would work to compress the image as well as possible.

**Part Two: Tree abstraction / Implementing compression**

Files to submit: QuadTreeImpl.java, QuadTreeImplTest.java

As can be seen from the QuadNode specifications, QuadNode implementations don’t necessarily obey the invariants outlined for a quad tree. One could imagine that users of the interface would be able to manipulate the QuadNode (by setting quadrants) leaving it in an inconsistent state (e.g. has some children, has both children and color etc.). Instead we want to package a quad tree constructed through QuadNodes so that it only exposes methods and operations that would still keep the tree state consistent.

For this section, you only need to implement the constructor for the quad tree. This constructor should be able to take in an array of image data (integers) and, using your implementation of QuadNode, build a tree that satisfies the quad tree invariants. You can use package-private helper methods here (and we encourage you to do so). We’re leaving this part of the design up to you, so make sure to spend some time planning out how you want to build things. There are many ways to structure your implementations - some will make your life much easier.

**Part Three: Tree Factories (6 points)**

Files to submit: QuadTreeFactoryImpl.java, QuadTreeFactoryImplTest.java

Now that you’ve implemented concrete classes for the quad tree interfaces, we need a way for you to offer your implementations for external use. Now, one certainly could just provide the constructors of the implementation classes to the public. However, doing that makes the external code dependent on your internal implementation details and thus hinders future refactoring of the code.

Instead, we can use the factory method pattern in Java. A factory is a class that creates objects through its namesake “factory” methods. Generally, a factory creates instances of a particular interface. Why is this useful? This allows us to receive an instance of an interface without knowing
what the concrete class is. In our case, we have an interface, QuadTreeFactory for a factory that builds QuadTrees. In our concrete implementation, QuadTreeFactoryImpl, we might choose to return MyFancyQuadTree or MySeventeenthAttemptAtAQuadTree. This is how we were able to write the SimplePaint program without knowing about your concrete QuadTree class.

In this assignment, you are asked to implement the buildFromIntArray method of the factory. Traditionally, computer monitors render the image from top to bottom by filling in each line, so in computer graphics, a flipped coordinate system with the y-axis pointing downwards is used to coordinate points in the image. This means that (0,0) will be referring to the top left corner of the image. The imageData array you’ll be expecting will also be oriented as a series of ‘scanlines’. For example, imageData[0][x] would refer to the scanline at (x,0), imageData[1][x] would be (x,1) etc. You can also have a look at buildFromImage() in SimplePaint to figure out how this works. For example, with the following array

```java
int [][] image = {
    {0, 1, 2},
    {3, 4, 5},
    {17, 18, 19}};
```

we can access the value 17 with image[2][0], which corresponds to x, y coordinates (0, 2). In linear algebra, this coordinate addressing scheme is also known as row-major order.

Part Four: Finishing up the tree abstraction (23 points)

Files to submit: QuadTreeImpl.java, QuadTreeImplTest.java

Now that we’ve done the lower-level implementation of the compression tree, we can move onto implementing more interesting methods on the compression tree itself. You will notice that QuadTree.java has a getCompressionRatio() stub. Let us now focus on that. The compression ratio is \( \frac{N}{P} \), where \( N \) is the total number of nodes in the tree and \( P \) is the number of pixels in the image.

For example: Given an image with \( n \) pixels...

- ...that is purely one color: An optimal tree will have one node, with compression ratio \( \frac{1}{n} \). See the first example in Figure 1.

- ...that is half black, half white: An optimal tree would limit itself to five nodes, one for the root and four quadrants as leaves. In this case, the optimal compression ratio is \( \frac{5}{n} \). See the second example in Figure 1. Note what this implies about counting nodes: When there is a non-leaf, it, as well as its children, are included in the count.

You should be able to get the node count from getSize(), and you should be able to easily calculate the number of pixels in the image from getDimension() (both are methods of the QuadNode interface).
The compression ratio is a good way for programs to determine when to use compression and when not to. For images without any uniform colored regions, quad trees not only cannot effectively compress them, a quad tree will incur extra overhead which can bring the number of nodes over the number of pixels. Programs in real life scenarios would look at this value and decide whether compressing was worth it.

Part Five: Decompression (13 points)

Files to submit: QuadTreeImpl.java, QuadTreeImplTest.java

Because this compression algorithm is lossless, it is possible to recover the original array of RGB combined values from the compressed quad tree with no loss of information. The `decompress()` method on the `QuadTree` class is meant to provide this functionality. Implement the method stub.

As a result of implementing this method correctly, we would expect that the original pixel array and the decompression array of the compression tree of the original pixel array should exactly equal each other for all coordinate pairs.

Part Six: Retrieving pixel color and editing the image (29 points)

Files to submit: QuadTreeImpl.java, QuadTreeImplTest.java

Implement the method `getColor` in the in your `QuadTree`. This method receives integer coordinates `x` and `y` as input (refer to the previously outlined coordinate system). The method returns the color of the pixel at coordinate `(x, y)` of the image represented by the `QuadTree`. Please implement this method in-place: in other words, do not convert the quadtree into an array and then index into the array. Traverse the quadtree instead; it’s asymptotically faster and more space-efficient.

Next, write the method `setColor` in the class `QuadTree`. This method has three inputs: a color, and two integer coordinates `x` and `y`. This method is trickier than the previous one in that it performs an in-place modification of the quad tree. You should always keep the quad tree optimal (i.e. no node should have four children of the same color) which may require compressing nodes or expanding them. You should not have to decompress the whole quad tree in the process of editing the image. As a hint, you may find some overlap with the logic of building the tree from an array source. These similarities may be great candidates to abstract out as helpers. Remember that you’re in charge of designing your implementation.

After implementing this method, you can arbitrarily edit the image without needing to decompress it! That’s pretty cool.

Style & Tests (15 points)

The above parts together are worth a total of 85 points. The remaining 15 points are awarded for code style, documentation, and sensible tests. Style is worth 5 of the 15 points, and you will be
graded according to the 121 style guide.

You will need to write comprehensive unit test cases for each of the classes and methods you implement. Make sure you consider edge cases and exceptional cases, i.e. the more “interesting” inputs and situations.

Each unit test should test a single simple aspect of a class, i.e. how one specific method behaves. Prefer many small tests over cramming a bunch of asserts into a single test method. Be sure to demonstrate that you considered “bad” inputs such as null inputs. Your test cases will be manually graded by the TAs, and are worth 10 of the 15 points. You will have to thoroughly test your code to get full points! This includes testing any helper methods you have written.

Unit tests are extremely important for this and future homeworks. These tests guarantee that individual parts of your program function correctly. Writing good tests are to your own benefit. Our automated tests, like any other application that uses the interfaces, will only test compliance to the interface documentation and cannot test your implementation details. As such, they will not give partial credit for any cascading errors (i.e. an error that didn’t get caught in your `QuadNode` unit tests may manifest as multiple failures and point deductions when testing the tree). You are responsible for testing each component in your implementation.

Note: You will not be able to write JUnit test cases for any private methods. Instead, make them package-private by leaving off any privacy modifier.

Simple paint!

Files to submit: None

You will notice that we have included a `SimplePaint` class. This is a self-contained simple paint application that uses a `QuadTree` to store an image and allow you to make edits to it by drawing with your mouse. The paint program is built on top of the interfaces provided by quad trees.

At this point, you should be able to run the program flawlessly. Play around with opening some test images or images of your own. You can also turn on node borders look at your quad tree structure through this application.

This part is simply meant to be for fun, and there’s no need to include this in unit tests (nor is there a very obvious way to do so). We’ve included a few test images in `res/` so that you can see how the quad tree compression performs for different types of images. You may also refer to them for any end-to-end testing you wish to do on your own (e.g. Read in an image, compress it and then decompress it and write it out etc.). End-to-end tests are not required as they will be the kind of tests that we perform when grading your submission.