HW 6: Image Processing

Images are all around us, and so is image processing. Each time you move, crop, rotate, or resize an image, you are using image processing algorithms. In this homework assignment you will learn about, and implement, some of the most commonly used image processing functions. These functions lie at the very core of programs like Instagram and Photoshop.

As you implement these capabilities, you will continue to develop two key programming skills: handling two-dimensional arrays, and understanding modularity. You will also get a hands-on introduction to creating and using simple *objects*. This will provide a gentle hands-on introduction to object-oriented programming, a subject that we will take up in the second part of the course.

For an entertaining behind-the-scenes view of digital images, take a look at this TED talk. Ignore the nerdy humor and focus on the essence, which is quite instructive.

Image processing is an exciting field of theory and practice, and we hope that you will enjoy cutting your teeth into it. We begin by introducing some basic concepts. Note that this long document is not just a homework document; It is also a hands-on tutorial of *Image Processing*, an introduction to *Object-Oriented Programming*, and a solid practice in working with 2D arrays.

1. Digital Imaging

Color

Color is a human perception of a light wave that has a certain wavelength. The human brain can distinguish between about 10 million different wavelengths, and human languages have given a few of these wavelengths names like *red*, *yellow*, *green*, and so on (notice the conceptual similarity to naming selected sound waves like *do*, *re*, *mi*, etc.). When light waves hit the human eye, specialized cells in the retina react to them according to their wavelengths. The human retina features three types of such sensor cells, each specializing in detecting different spectrums of wavelengths. Those wavelengths correspond to what we are used to call *Red*, *Green*, and *Blue* (RGB). All the fantastic colors that we are fortunate to see around us emerge from the way our brain mixes and combines different *intensities* ("volumes", as we say in Hebrew) of those three basic colors.

The natural mechanism described above gives rise to a mathematical model (but not the only one) for representing colors. We can view each color as a vector of three integer values, each ranging between 0 and 255. Those three numbers are used to represent the *intensities* of the three basic colors Red, Green, and Blue. Thus, mathematically, every color is a triplet of numbers $\langle r, g, b \rangle$, where each of these values ranges from 0 to 255. We see that the RGB system can represent 256^3=16,777,216 different colors. This is about 6 million more colors than the human brain can discern. Not bad.

`Color` objects: In Java, colors can be represented as instances of a class called `Color`. Another way of saying this is that "In Java, colors are represented as objects of type `Color`". Unlike primitive types like `int` and `double`, the type `Color` is not part of the basic Java language. Rather, it is implemented by a class named `Color`, which is part of the standard class library that extends the basic Java language. How classes can be made to represent new data types is something that we will learn later in the course. For now, suffice it to say that the Java class library features many such classes, and `Color` is one of them (`String` is another example of a class in the Java class library).

The color objects are quite similar to arrays. For example, the following code declares and constructs six color objects:

```
Color red     = new Color(255,  0,  0);
Color green   = new Color(  0,255,  0);
Color blue    = new Color(  0,  0,255);
Color black   = new Color(  0,  0,  0);
Color white   = new Color(255,255,255);
Color yellow  = new Color(255,255,  0);
```

For example, the first statement says: "declare a reference variable named `red`, of type `Color`, and make it refer to a memory block where the three numbers `255`, `0`, and `0` are stored".

In object-oriented programming, the data items of an object are accessed using methods called "getters". Here is an example of using these getters:

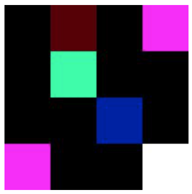
```
System.out.println(yellow.getRed());   // Prints 255
System.out.println(yellow.getGreen()); // prints 255
System.out.println(yellow.getBlue());  // prints 0
```

In object-oriented programming, a function that operates on an object is called *method*. The above example illustrates calling three methods on the same `Color` object, referred to by the variable `yellow`. As we see from the comments, each of these methods is designed to return an `int` value. This method calling illustrates a key difference between accessing array data and accessing object data. If we were to use an array named `yellow` for representing the color's data, we could get the RGB values by accessing `yellow[0]`, `yellow[1]`, and `yellow[2]`, respectively. If we use a `Color` object instead, as we do here, we don't access these values directly; Instead, we access them using the three *get* methods. We will have much more to say about this style of object-oriented programming later in the course.

Here is the [Color class API](). The only `Color` methods that we will use in this project are the `getRed`, `getGreen,and getBlue` methods, so there is no need to review any other methods in this API.

Image

A digital image can be viewed as a grid of RGB values. For example:



```
(  0,  0,  0) (100,  0,  0) (  0,  0,  0) (255,  0,255)
(  0,  0,  0) (  0,255,175) (  0,  0,  0) (  0,  0,  0)
(  0,  0,  0) (  0,  0,  0) (  0, 15,175) (  0,  0,  0)
(255,  0,255) (  0,  0,  0) (  0,  0,  0) (255,255,255)
```

This little image can be implemented in Java as a 2D array of `Color` objects, as follows:

```
Color[][] tinypic = {
                      { new Color(  0,  0,  0), ... , new Color(255,  0,255) } ,
                      { new Color(  0,  0,  0), ... , new Color(  0,  0,  0) } ,
                      ...
                      { new Color(255,  0,255), ... , new Color(255,255,255) } ,
                    }
```

Following this declaration / initialization, every array element `tinypic[i][j]` refers to a `Color` object. In image processing applications, these array elements are called *pixels* (short for *Picture Elements*).

The image *resolution* is determined by how many pixels it contains. The more pixels, the sharper and more detailed the image. Typically, an image array contains hundreds of rows and hundreds of columns. Physically speaking, each pixel is drawn on the screen (or printed on paper) using a tiny physical area. The image shown above, which is made of only 16 pixels, was blown up 5000% before we plugged it into this document.

We note in passing that if you are a great artist, you can get a lot of expression from just a few pixels. For example, consider this low resolution yet pretty good portrait of Abraham Lincoln, made by Salvador Dali.

Image files

In order to store images persistently, and transfer them from one computer to another, we use *files*. Clearly, we must decide on some standard way to format such image files. In this homework we use a simple standard image file format called PPM (*Portable Pixel Map*). For example, the PPM file of our `tinypic` image is as follows:

```
P3
4 4
255
  0   0   0   100   0   0     0   0   0    255   0 255
  0   0   0     0 255 175     0   0   0      0   0   0
  0   0   0     0   0   0     0  15 175      0   0   0
255   0 255     0   0   0     0   0   0    255 255 255
```

The first three lines are called *file header*. P3 is an agreed-upon code that says “I am a PPM file”. Next come the numbers of columns and the number of rows in the image (in this example, 4 by 4). Next comes the maximum color code value in this image, which happens to be 255.

Following the file header comes the *body*. The body contains all the pixel values. Every three consecutive numbers represent a single pixel. White space is commonly used to make the data more readable to programmers, and is ignored by computers. Following convention, each row of pixels starts in a new line.

The PPM file format is recognized by most image editors and image viewing apps. When you double-click a `.ppm` file on your computer, most likely it will be displayed as an image. In order to see the RGB values that drive this image (the numbers), open the `.ppm` file using a text editor. At this stage we recommend that you take a look at some of the `.ppm` files supplied with this homework.

There are numerous different file formats for storing digital images. JPEG, GIF, and PNG are popular examples, designed for specific needs. In order to cut down storage and communications costs, these file formats represent images in a compressed way (something we'll learn later in the course). PPM files use no compression, making them easy to work with.

2. Getting Started

Start by compiling, running, and understanding the supplied `ColorDemo` class. This class illustrates how to construct and print `Color` objects. It also illustrates how to construct arrays of `Color` objects. When you are done playing with `ColorDemo`, we recommend that you spend a few minutes practicing mixing colors.

In this homework assignment you will gradually develop a library of image editing functions. You will also write client code for testing and playing with these functions, and enjoying the fruits of your work. Before doing anything though, read this entire document. There is no need to understand everything you read; this understanding will grow on you as you start working on the code.

So, assuming that you've read the entire document, take a look at the supplied `Runigram.java` class. We now turn to describe the functions in this class.

Displaying an image: You will notice that the supplied `Runigram` class features two fully-implemented functions named `setCanvas` and `display`. These functions handle the rendering (display) of images that are implemented as 2D arrays of `Color` values. They do so by calling functions from the `StdDraw` class. At this stage, there is no need to understand how these two functions work. Instead, you only have to understand how to use them as black box abstractions.

Printing an image: In addition to rendering images graphically, developers of image processing applications test and debug their work by inspecting the image's data – the RGB values – directly. In our implementation, this service is performed by a function named `print`, which is essential for testing and debugging purposes. When we will start implementing various image editing functions, we will test them on small images, consisting of just a few rows and columns of pixels. The `print` function will enable you to inspect the numbers and check that your functions are doing what they are supposed to do. For example, here is a typical testing sequence:

```
// Tests the reading of an image from a file:
int[][][] image = read("tinypic.ppm");
print(image);   // prints the image data
```

We now turn to describe these `read` and `print` functions.

Reading an image from a file

The function `Color[][] read(String filename)` receives the name of a PPM file and returns a 2D array containing the image data. The `.ppm` file must be located in the program folder.

Complete the implementation of the `read` function. The `print` function, described next, will be used to test your `read` function implementation.

Implementation tips: (0) To get started, compile the given classes `In.java`, `StdDraw.java`, and `ColorDemo.java.` (1) The `read` function (that you have to complete) creates a 2D array of `Color` values. The given `ColorDemo` class performs similar actions, so take a look at its code. (2) Note that the `read` function returns the 2D array that it created.

Printing an image

The void function `print(Color[][] image)` prints the `Color` values of a given image. For example, here is the result of printing the `tinipic` image (after reading it, of course, from the `tinypic.ppm` file, using the `read` function):

```
(  0,  0,  0) (100,  0,  0) (  0,  0,  0) (255,  0,255)
(  0,  0,  0) (  0,255,175) (  0,  0,  0) (  0,  0,  0)
(  0,  0,  0) (  0,  0,  0) (  0, 15,175) (  0,  0,  0)
(255,  0,255) (  0,  0,  0) (  0,  0,  0) (255,255,255)
```

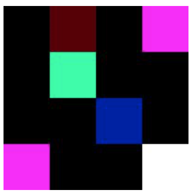
Complete the implementation of the `print` function (in `RuniGram.java`). Use / modify the code of the `main` function to test your implementation of the `read` and `print` functions.

Implementation tip: To print `Color` values, use the given (overloaded) `print(Color c)` function. To print a 2D array of `Color` values, iterate through the array elements and print each element individually. Your output should be formatted exactly the same as the example shown above.

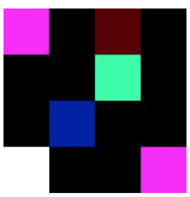
3. Basic Image Processing

Horizontal Flipping

The function `Color[][] flippedHorizontally(Color[][] image)` creates and returns a new image which is a horizontal flip of the given image: In each row of the new image, the order of the pixels is reversed (within each pixel though, nothing changes). For example, here is the `tinypic` image (top) and its horizontally flipped version:



```
(  0,  0,  0) (100,  0,  0) (  0,  0,  0) (255,  0,255)
(  0,  0,  0) (  0,255,175) (  0,  0,  0) (  0,  0,  0)
(  0,  0,  0) (  0,  0,  0) (  0, 15,175) (  0,  0,  0)
(255,  0,255) (  0,  0,  0) (  0,  0,  0) (255,255,255)
```



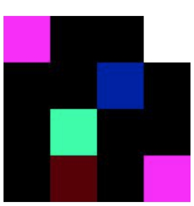
```
(255,  0,255) (  0,  0,  0) (100,  0,  0) (  0,  0,  0)
(  0,  0,  0) (  0,  0,  0) (  0,255,175) (  0,  0,  0)
(  0,  0,  0) (  0, 15,175) (  0,  0,  0) (  0,  0,  0)
(255,255,255) (  0,  0,  0) (  0,  0,  0) (255,  0,255)
```

Write the `flippedHorizontally` function. Test it by playing with the code of the `main` function. Note that the code for testing the `flippedHorizontally` function is already given in `main`.

Implementation tip: Start the function's code by creating a new image (a 2D array of `Color` objects) that has the same dimensions as the given image. Then fill the new image with the correct values. Finally, terminate the function's code by returning this new image. ***These two tips apply to all every function in this class that returns a new image.***

Vertical Flipping

The function `Color[][] flippedVertically(Color[][] image)` returns a new image which is a vertical flip of the given image: In each column of the new image, the order of the pixels is reversed. For example, the vertically flipped version of `tinypic` is as follows:



```
(255,  0,255) (  0,  0,  0) (  0,  0,  0) (255,255,255)
(  0,  0,  0) (  0,  0,  0) (  0, 15,175) (  0,  0,  0)
(  0,  0,  0) (  0,255,175) (  0,  0,  0) (  0,  0,  0)
(  0,  0,  0) (100,  0,  0) (  0,  0,  0) (255,  0,255)
```

Write the `flippedVertically` function. Test it by playing with the code of the `main` function.

Grey Scaling

The RGB system has the following convenient property: When all the three color intensities are the same, the resulting color is a shade of gray, ranging from black (0,0,0) to white (255,255,255). The resulting 256 values are called "greyscale codes". With that in mind, "greyscaling" is a technique for transforming a colored image into a black and white image. It is advised to do it gracefully, in a way which is pleasant and sensible to the human eye. Below is an example of a colored image of a cupcake, and its greyscaled version:

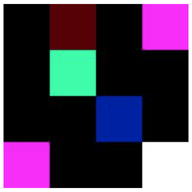
How to transform an RGB color code into a greyscale code that "represents" that color? Suppose that the RGB values (each being a number from 0 to 255) are represented by the values *r*, *g* and *b*. We define *luminance* to be the following linear combination:

$$lum(r, g, b) \;=\; (int)\,(0.299 \cdot r \;+\; 0.587 \cdot g \;+\; 0.114 \cdot b)$$

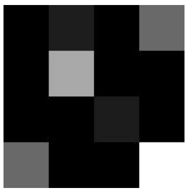
Since the luminance weights are positive and sum up to 1, and since the intensities are all integers between 0 and 255, the luminance ends up being an integer between 0 and 255. With that in mind, the resulting greyscale value is defined as (*lum*, *lum*, *lum*). Where did the weights 0.299, 0.587, and 0.114 come from? These weights are based on the human eye's sensitivity to red, green, and blue, and were determined after running experiments with human subjects who evaluated the perceieved quality of grayscaled versions of various color images.

We'll implement the greyscaling transformation in two steps. First, implement the function `Color luminance(Color c)`, that returns the greyscale color of the given color, using the formula presented above. Note that this function creates and returns a new `Color` object. To check that your function works correctly, you may consult this resource.

Next, implement the function `Color[][] greyScaled(Color[][] image)`. This function returns the greyscaled version of the given image. For example, here is the `tinypic` image and its greyscaled version:



```
(  0,  0,  0) (100,  0,  0) (  0,  0,  0) (255,  0,255)
(  0,  0,  0) (  0,255,175) (  0,  0,  0) (  0,  0,  0)
(  0,  0,  0) (  0,  0,  0) (  0, 15,175) (  0,  0,  0)
(255,  0,255) (  0,  0,  0) (  0,  0,  0) (255,255,255)
```



```
(  0,  0,  0) ( 29, 29, 29) (  0,  0,  0) (105,105,105)
(  0,  0,  0) (169,169,169) (  0,  0,  0) (  0,  0,  0)
(  0,  0,  0) (  0,  0,  0) ( 28, 28, 28) (  0,  0,  0)
(105,105,105) (  0,  0,  0) (  0,  0,  0) (255,255,255)
```

Test your implementation of the `greyScaled` function by playing with the code of the `main` function.

Editor 1

We now describe a given client class that uses the three image processing services described above. The `Editor1.java` class takes two command-line arguments: the name of a PPM file that represents an image, followed by one of the strings `fh` (flip horizontally), `fv` (flip vertically), or `gs` (gray scale). The program reads the input image from the specified file, and creates a new output image which is the result of applying the specified transformation. The program then displays the first image, waits a little bit, and displays the second image. For example, the following command creates and displays the vertical flip of an Iroman image.

```
% java Editor1 ironman.ppm fv
```

The `Editor1` program is given. Make sure that you understand how it works.

To stop the execution of a Java program that displays a graphical image: You can either (1) close the image window, or (2) press `CTRL-C` from the terminal.

4. Scaling

Quite often, we want to resize a given image. For example, reducing a given image into a small thumbnail image, zooming in on a satellite photograph, or making an image wider or taller. All these operations can be described as *scaling* either the width and/or the height of the image. For example, the left image below is 400 pixels wide by 600 pixels high. If we double its width and halve its height, we get the 800-by-300 image shown on the right.

The scaling algorithm is as follows. Let the width and the height of the source image be w_0 and h_0, and the width and height of the target image be w and h. Then pixel (i, j) of the target image should be set to pixel $(i \cdot \frac{h_o}{h}, j \cdot \frac{w_o}{w})$ in the source image. For example, if we are halving the size of an image, the scale factors are 2 in both dimensions. Therefore, and choosing an arbitrary pixel as an example, pixel (2, 3) of the scaled version should be set to pixel (4, 6) of the source image.

The scaling operation is implemented by the function `Color[][] scaled(Color[][] image, int width, int height).` The function returns a new image which is a version of the original image, scaled to be of the given width and height. For example, `tinypic` is a 4 x 4 image. We can scale it to a 3 x 5 image by calling `scaled(tinypic,3,5).` Below we see the data of the original image (top) and its scaled version (bottom). You can work out the proportion factors and verify that the scaled image is built correctly.

```
(  0,  0,  0) (100,  0,  0) (  0,  0,  0) (255,  0,255)
(  0,  0,  0) (  0,255,175) (  0,  0,  0) (  0,  0,  0)
(  0,  0,  0) (  0,  0,  0) (  0, 15,175) (  0,  0,  0)
(255,  0,255) (  0,  0,  0) (  0,  0,  0) (255,255,255)
```

```
(  0,  0,  0) (100,  0,  0) (  0,  0,  0)
(  0,  0,  0) (100,  0,  0) (  0,  0,  0)
(  0,  0,  0) (  0,255 175) (  0,  0,  0)
(  0,  0,  0) (  0,  0,  0) (  0, 15,175)
(255,  0,255) (  0,  0,  0) (  0,  0,  0)
```

Implement the `scaled` function, and test it on the `tinypic` image. Notice that when we process small image files like `tinypic.ppm`, we don't display the result using a program like `Editor1` (we can do it, but the resulting image will be ridiculously small). Instead, you can display and inspect the image's data by calling the `print` method from the `main` method of `RuniGram`. When convinced that your code works correctly, continue to the next task (below).

Editor 2

This client class is designed to test the scaling operation just described. The class receives three command-line arguments: the name of the PPM file representing the image that should be scaled, and two integers that specify the width and height of the scaled image. For example:

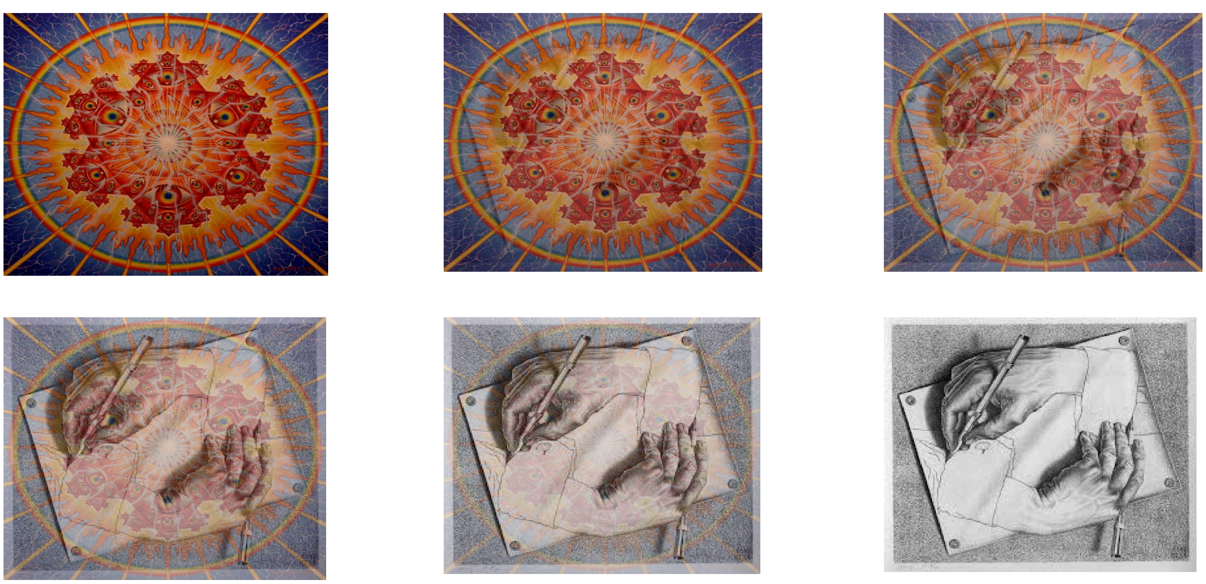
```
% java Editor2 ironman.ppm 800 500
```

Implementation tip: `Editor2.java` is quite similar to `Editor1.java`. The main difference is this: We cannot display the scaled image on the same canvas of the original image, since the two images have different dimensions (that's the whole point of scaling, isn't it?). Therefore, after reading the source image and creating the scaled image, `Editor2` should create a canvas for the source image, display the source image, pause for a few seconds, create a new canvas for the scaled image, and display the scaled image.

Implement and test the `Editor2.java` class. It should be fun to scale `Ironman` and some of the other PPM images in the exercise folder.

5. Morphing

We now turn to implement a striking visual effect called "morphing": Given a source image and a target image, we transform the former into the latter in a stepwise process that can be as smooth as we please. For example, here is an example of morphing a drawing by Alex Grey into a drawing by M.C. Escher, in 6 steps:



We will approach the morphing challenge by dividing it into several independent functions, which we now turn to describe.

Blending colors: a blend of two colors is a new color whose RGB values are weighted averages of the RGB values of the two input colors. The blending operation is parameterized by a real number $0 \leq \alpha \leq 1$ that determines how to blend the two colors: the weight of the first color is α, and the weight of the second color is $1 - \alpha$. For example, suppose that the two input colors are (100, 40, 100) and (200, 20, 40). Blending them with $\alpha = 0.25$ produces the color (175, 25, 55), as follows:

$$0.25 \cdot 100 + 0.75 \cdot 200 = 175$$

$$0.25 \cdot 40 + 0.75 \cdot 20 = 25$$

$$0.25 \cdot 100 + 0.75 \cdot 40 = 55$$

The function `Color blend (Color c1, Color c2, double alpha)` returns a new blended color according to the process described above. As usual, the resulting color consists of (rounded) integer values. Write and test the `blend` function. Notice that the `Runigram` class features two `blend` functions: one that operates on two colors, and one that operates on two images. Write and test the `blend` function that operates on two colors.

Blending images: Two images of the same dimensions can be blended by blending all the corresponding input pixels using a given α. The function `Color[][] blend (Color[][] image1, Color[][] image2, double alpha)` returns the alpha-blending of the two given images. The function computes each new pixel using the `blend` function that operates on two colors. Write and test the `blend` function that operates on two colors. Assume that the two source images have the same dimensions (there is no need to test this precondition).

Morphing: suppose we want to morph a source image into a target image gradually, in *n* steps. To do so, we stage a sequence of 0, 1, 2, ... , n steps, as follows. In each step i we blend the source image and the target image using $\alpha = (n - i)/n$. For example, here is what happens when $n = 3$:

step 0: Blend the two images using $\alpha = 3/3$ (yielding the source image)
step 1: Blend the two images using $\alpha = 2/3$
step 2: Blend the two images using $\alpha = 1/3$
step 3: Blend the two images using $\alpha = 0/3$ (yielding the target image)

The function `void morph(Color[][] source, Color[][] target, int n)` morphs the source image into the target image in *n* steps. If the images don't have the same dimensions, the function scales the target image to the dimensions of the source image, and then starts the morphing sequence. At the end of each blending step, the function should use the `Runigram.display` function to display the intermediate result, and the `StdDraw.pause` function to pause for about 500 milliseconds. Implement and test the `morph` function. Note: The canvas for this morphing operation is set by the caller of the `morph` function, as we now turn to discuss.

Editor 3

This client program tests the morphing operation described above. For example, consider the following program execution:

```
% java Editor3 cake.ppm ironman.ppm 50
```

This action transforms the cake into Ironman, in 50 steps. The greater the number of morphing steps, the smoother is the visual transition. The program starts by getting the three command-line arguments. Next, the program creates the source and the target images by calling the `read` function. Next, the program creates a canvas for displaying the images (this is done by calling the `Runigram.canvas` function). Finally, the program calls the `Runigram.morph` function. Implement the `Editor3.java` program.

Note that the drawing methods of `StdDraw` act globally on the same, *shared canvas*. That's why it is possible to have Editor3 create a canvas, and then have Runigram draw on it, as we do here. The `Editor3.java` program is given.

Editor 4

This client program performs another striking visual effect: it morphs an image into its grescaled version. For example:

```
% java Editor4 thor.ppm 50
```

This action transforms the colored Thor image into a black and white Thor image.

Implement the `Editor4.java` program, and test it. Sit back, watch, and enjoy.

Implementation tips: The skeleton of the `Editor4.java` class is not given. You should write, document, and implement it yourself, from scratch. It's quite similar to `Editor3.`

Submission

Before submitting your work for grading, make sure that your code is written according to our [Java Coding Style Guidelines](). Submit the following filed only:

- `Runigram.java`
- `Editor1.java`
- `Editor2.java`
- `Editor3.java`
- `Editor4.java`

Submission deadline: December 22, 23:55.