

# Programming Assignment 1

CS 474

<https://github.com/alexander-novo/CS474-PA1>

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## Contents

<b>1</b>	<b>Image Sampling</b>	<b>2</b>
<b>2</b>	<b>Image Quantization</b>	<b>2</b>
<b>3</b>	<b>Histogram Equalization</b>	<b>2</b>
3.1	Theory . . . . .	2
3.2	Implementation . . . . .	2
3.3	Results and Discussion . . . . .	3
<b>4</b>	<b>Histogram Specification</b>	<b>5</b>
4.1	Theory . . . . .	5
4.2	Implementation . . . . .	6
4.3	Results and Discussion . . . . .	6
	<b>Code Listings</b>	<b>9</b>

# 1 Image Sampling

# 2 Image Quantization

# 3 Histogram Equalization

## 3.1 Theory

It is desirable to have high contrast in an image, as it allows you (and a computer vision algorithm) to pick out details more easily. In general, images whose histograms have a uniform distribution tend to have high contrast - especially when compared with images with a central mode (represented by a central “hump” in the histogram). To convert a (continuously distributed) random variable  $X$  to a uniform distributed random variable  $Y$ , we simply apply the transformation

$$Y = F_X(X),$$

where  $F_X$  is the CDF (cumulative distribution function) of  $X$ . As a transformation of the variable  $X$ , we know then that the PDF (probability density function) of  $Y$  is

$$f_Y(y) = f_X(F_X^{-1}(y)) \left| \frac{d}{dy} F_X^{-1}(y) \right|,$$

and by the inverse function theorem of calculus,

$$\begin{aligned} &= f_X(F_X^{-1}(y)) \left| \frac{1}{F_X'(F_X^{-1}(y))} \right| \\ &= f_X(F_X^{-1}(y)) \left| \frac{1}{f_X(F_X^{-1}(y))} \right| \\ &= 1, \end{aligned}$$

so  $Y \sim \mathcal{U}(0, 1)$ . Of course, this only applies to continuous random variables, but we hope that a similar behaviour can be observed in discrete random variables. Unfortunately, since all pixels fall into a certain number of “bins” in the image’s histogram (based on the quantization level of the image), the transform can’t decrease the number of pixels in a bin. Instead, it can only spread bins out in the histogram and consolidate multiple bins into one, increasing the number of pixels in a bin. Therefore, if there are noticeable modes in the original image’s histogram, there will still be noticeable modes in the equalized histogram. As well, image quality will drop due to the spreading out and consolidating of bins effectively quantizing the image.

Since this behaviour comes from the approximation of continuous distributions by discrete distributions, the better an approximation is, the less noticeable these effects become. Therefore, increasing the quantization level of an image will make the process more effective, causing the output image’s histogram to be more like a uniform distribution.

## 3.2 Implementation

An array of integers is used for the image’s histogram, which is calculated by looping over the image’s pixels and incrementing the bin whose index is given by the pixel’s intensity value. Then, the CDF

is calculated by iteratively summing over the calculated histogram, using the recurrence relation for discrete CDFs:

$$\begin{aligned}
 F_X(x) &= \sum_{i=-\infty}^x P(X = x) \\
 &= P(X = x) + \sum_{i=-\infty}^{x-1} P(X = x) \\
 &= P(X = x) + F_X(x - 1),
 \end{aligned} \tag{1}$$

where  $P(X = x)$  is the histogram value of the intensity  $x$ . Since pixel intensities have finitely many values (and therefore a minimum value),  $F_X(x - 1) = 0$  for some  $x$  (the minimum intensity) and  $F_X(x) = P(X = x)$ .

The CDF is never converted to its normalized version. Instead, when applying the transformation, each resulting transformed pixel is multiplied by the normalization constant. This is to prevent accumulation of round-off errors until the final integer pixel value is calculated.

Since the calculation of the original histogram and the transformation is embarrassingly parallel, OpenMP is used to parallelize.

The source code for this implementation can be found in listing 6.

### 3.3 Results and Discussion

Figure 1 shows the result of applying the algorithm to the image `boat.pgm`. There is a noticeable difference in contrast - especially in the water, which is much clearer, and the shadows on the sail. However, there is some noise introduced in the sky, and loss of detail on the coast.



Figure 1: A comparison of `boat.pgm` with its equalization (right).

Figure 2 compares the original histogram of `boat.pgm` with the histogram of the new equalized image. As discussed in section 3.1, the new histogram is not that of a uniform distribution, but there are some notable improvements over the original histogram. Firstly, the bins concentrated around the various modes have become sparser, so while the modes still exist with the same number of pixels in their bins (as discussed earlier), there are fewer pixels in the region of the bin. As well, a couple of the modes have spread out, making them easier to differentiate between. Finally, the bins in lower regions of the histogram have concentrated so they aren't as low compared to the modes.

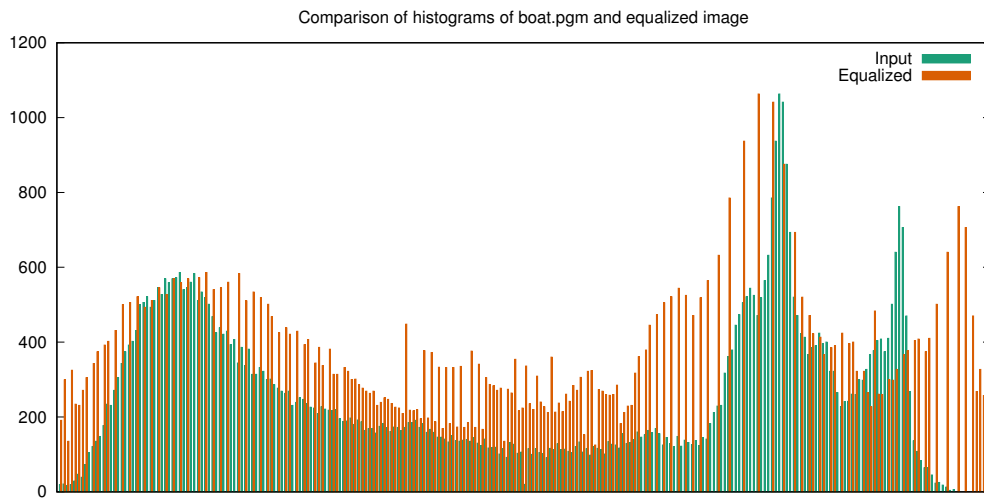


Figure 2: A comparison of histograms of `boat.pgm` and its equalized version

Figure 3 shows the result of applying the algorithm to the image `f_16.pgm`. There's a drastic increase in contrast in the clouds, but the results around the text on the plane are a mixed bag - the "U.S. AIR FORCE" text in the middle of the plane has good increase in contrast, while the "F-16" text on the tail has a decrease in contrast. As well, there is loss of detail on the mountains and the aberration along the left and lower rims of the image.

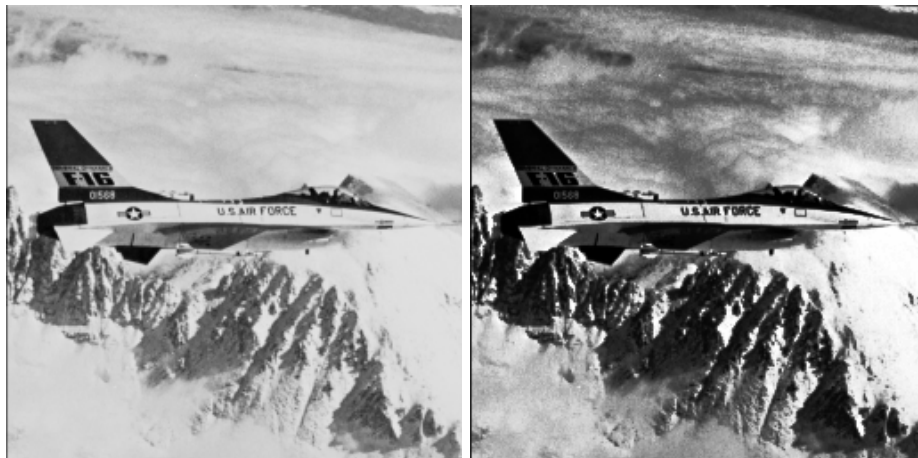


Figure 3: A comparison of `f_16.pgm` with its equalization (right).

Figure 4 compares the original histogram of `f_16.pgm` with the histogram of the new equalized image. The sparseness of bins and consolidation of bins is more apparent than in the previous example, especially around the mode of the image. This probably accounts for the loss of detail in the image, since most of the notable loss of detail happened in brighter regions of the image. These regions all got placed into the same bin, causing them to lose contrast and detail.

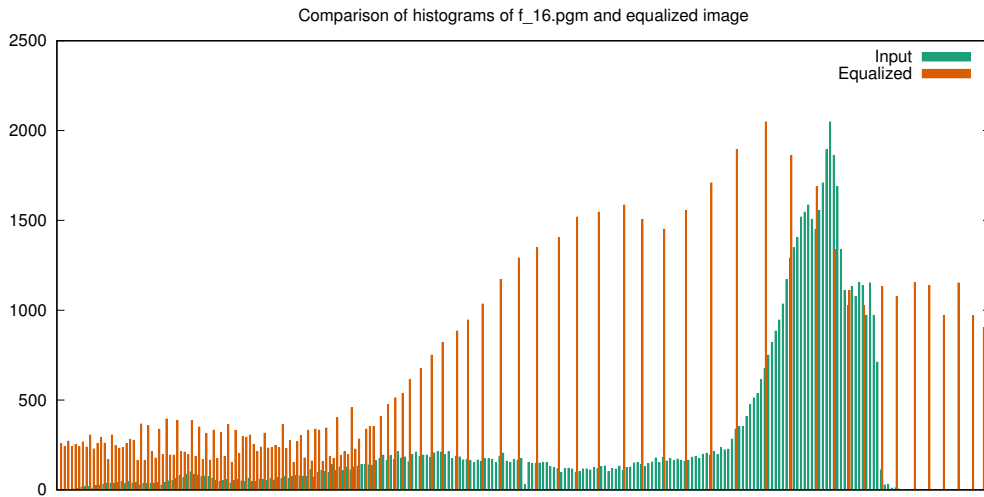


Figure 4: A comparison of histograms of `f_16.pgm` and its equalized version

The source code for generating these histogram comparison figures can be found in listing 8.

## 4 Histogram Specification

### 4.1 Theory

As demonstrated in section 3.3, we can transform images to have a similar distribution of pixel intensities as a uniform distribution by using the CDF of the image. Since CDFs are monotonically increasing, the pre-image of a single point is always a continuous interval, and when the CDF is strictly increasing (as is usually the case), the pre-image of a single point is also a single point. In this way, we can naturally define an “inverse” CDF

$$Q_X(x) = \inf F_X^{-1}(\{x\}), \quad (2)$$

known as the “quantile” function. Note that for discrete distributions, the infimum is equal to the minimum, and is chosen because CDFs are right-continuous (so in a discrete distribution, the minimum is always a possible value). Using the quantile function, we can transform a uniform distribution back to the original distribution. In this way, for two distributions  $X$  and  $Y$ ,  $F_X$  transforms  $X$  to a uniform distribution and  $Q_Y$  transforms a uniform distribution back to  $Y$ , so  $Q_Y \circ F_X$  transforms  $X$  to  $Y$ , demonstrated in fig. 5.

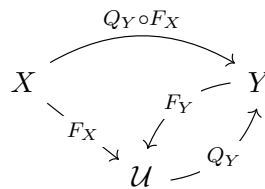


Figure 5: A commutative diagram showing how to map from one distribution to another using their CDFs.

In this way, we can perform an image transformation similar to histogram equalization, but with a supplied distribution instead of just a uniform distribution. This can be used for a similar effect as histogram equalization, but with a handpicked distribution to help avoid detail loss like in histogram equalization.

Similarly to histogram equalization, the math isn't exact for discrete distributions, but we can think of discrete distributions as approximations of continuous distributions. There are similar problems with this approximation as with the one made for equalization, but these problems can be lessened with increased quantization levels.

## 4.2 Implementation

The CDFs of the input image and input histogram are calculated in the same way as detailed in section 3.2. Then, each pixel's intensity is normalized with the input image's normalization constant and unnormalized with the input histogram's normalization constant. This step can be avoided if the images share a normalization constant - notably, when they are the same size and quantization levels. The quantile function (eq. (2)) is then calculated on the unnormalized value using a binary search on the input histogram's CDF. This is done, rather than calculating the quantile function for every possible value, to save memory and because a binary search can take advantage of the sorted nature of the calculated CDF.

The source code for this implementation can be found in listing 7.

## 4.3 Results and Discussion

Figure 6 shows the results of specifying `boat.pgm` to `sf.pgm`'s histogram. Since `sf.pgm` has much less contrast than `boat.pgm` and fewer extremely dark/light pixels, there is a huge loss of detail.



Figure 6: A comparison of `boat.pgm` with its specification to `sf.pgm` (right).

Figure 7 compares the histograms of `boat.pgm`, `sf.pgm`, and the specified output above. As can be seen, the algorithm does a much better job at matching the given histogram than matching a uniform distribution. From just a cursory glance at the comparison, it is hard to tell the output image's histogram apart from the input histogram. This is because the input histogram occupies a narrower band of intensities and has higher peaks than the input image's histogram, allowing the algorithm to consolidate bins effectively. This can be demonstrated by the areas where the algorithm fails to transform the histogram well - near the right side of the histogram - since this region of the input image's histogram is much larger than the input histogram. The reverse transformation would likely not be nearly as successful.

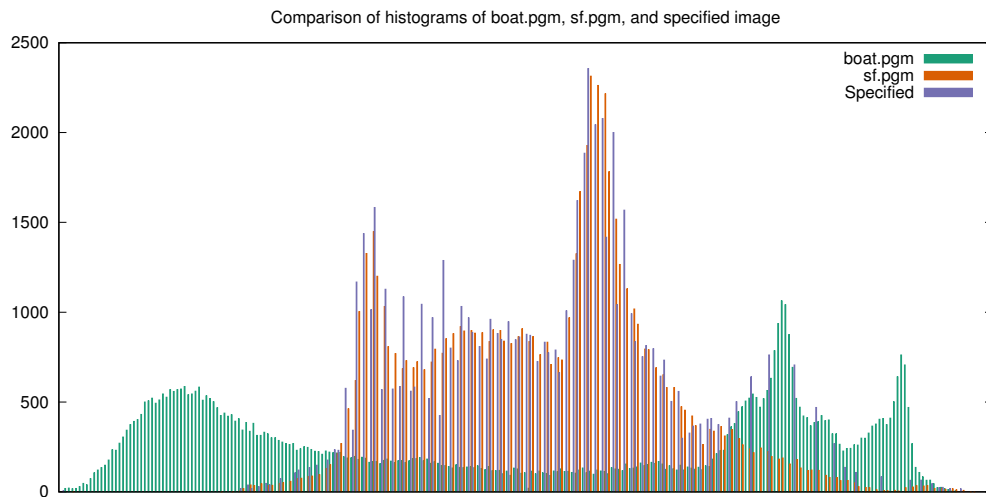


Figure 7: A comparison of histograms of `boat.pgm`, `sf.pgm`, and the specified output as seen in fig. 6.

Figure 8 shows the result of specifying `f_16.pgm` to `peppers.pgm`'s histogram. Since `peppers.pgm` has a large number of purely black pixels, a similar amount of pixels in `f_16.pgm` are converted to be purely black and there is a resulting large amount of detail loss - especially around darker regions.

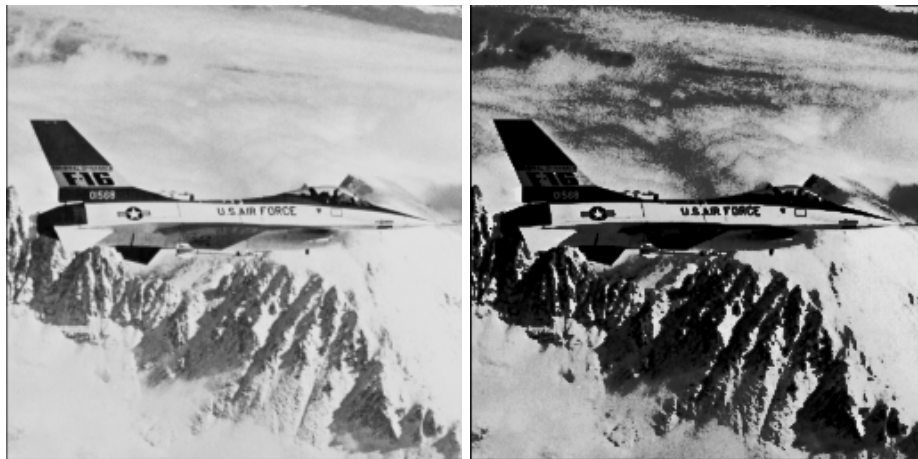


Figure 8: A comparison of `f_16.pgm` with its specification to `peppers.pgm` (right).

Figure 9 compares the histograms of `f_16.pgm`, `peppers.pgm`, and the specified output above. This gives a better look at the strengths and weaknesses of the algorithm - wherever the input image's histogram is below the input histogram (such as to the left), the algorithm succeeds in replicating the input histogram. In other regions (such as to the middle and right), the algorithm can only space out the bins to make the average density in a region similar.

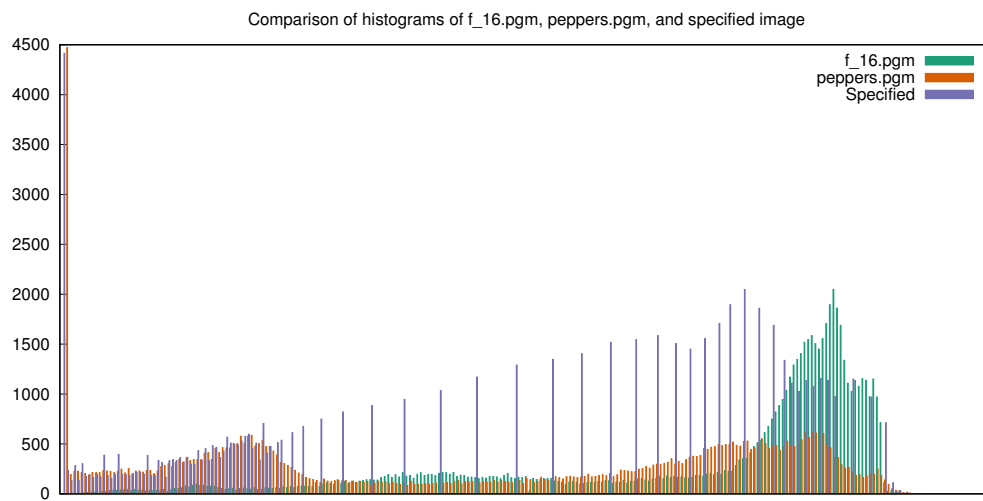


Figure 9: A comparison of histograms of `f_16.pgm`, `peppers.pgm`, and the specified output as seen in fig. 8.



## Code Listings

1	Header file for the common <code>Image</code> class. . . . .	9
2	Implementation file for the common <code>Image</code> class. . . . .	10
3	Implementation file for the <code>Histogram</code> supporting library. . . . .	13
4	Implementation file for the <code>sample</code> program. . . . .	14
5	Implementation file for the <code>quantize</code> program. . . . .	15
6	Implementation file for the <code>equalize</code> program. . . . .	17
7	Implementation file for the <code>specify</code> program. . . . .	21
8	<code>gnuplot</code> plotting file for generating two-histogram comparison plots. . . . .	27
9	<code>gnuplot</code> plotting file for generating three-histogram comparison plots. . . . .	28

Source code can also be found on the project's GitHub page: <https://github.com/alexander-novotny/CS474-PA1>.

Listing 1: Header file for the common `Image` class.

```

1  // Common/image.h
2  #pragma once
3
4  #include <iostream>
5
6  class Image {
7  public:
8      // The type that is used for the value of each pixel
9      // As of right now, read and operator<< only work if it is one byte large
10     typedef unsigned char pixelT;
11     // Struct for reading just the header of an image
12     struct Header {
13         enum Type {
14             COLOR,
15             GRAY,
16         } type;
17
18         unsigned M, N, Q;
19
20         // Read header from file
21         // Throws std::runtime_error for any errors encountered,
22         // such as not having a valid PGM/PPM header
23         static Header read(std::istream &in);
24     };
25
26     Image();
27     Image(unsigned, unsigned, unsigned);
28     Image(const Image &); // Copy constructor
29     Image(Image &&);      // Move constructor
30     ~Image();
31
32     // Read from stream (such as file)
33     // Throws std::runtime_error for any errors encountered,
34     // such as not being a valid PGM image
35     static Image read(std::istream &in);
36

```

```

37 // Output to stream (such as file)
38 friend std::ostream &operator<<(std::ostream &out, const Image &im);
39
40 // Pixel access - works like 2D array i.e. image[i][j]
41 pixelT *operator[](unsigned i);
42 const pixelT *operator[](unsigned i) const;
43 Image &operator=(const Image &rhs); // Assignment
44 Image &operator=(Image &&rhs);      // Move
45
46 // Read-only properties
47 pixelT *const &pixels = pixelValue;
48 const unsigned &rows = M;
49 const unsigned &cols = N;
50 const unsigned &maxVal = Q;
51
52 private:
53 Image(unsigned, unsigned, unsigned, pixelT *);
54 unsigned M, N, Q;
55 pixelT *pixelValue;
56 };
57
58 std::ostream &operator<<(std::ostream &out, const Image::Header &head);

```

Listing 2: Implementation file for the common Image class.

```

1 // Common/image.cpp
2 #include "image.h"
3
4 #include <cassert>
5 #include <cstdlib>
6 #include <exception>
7
8 Image::Image() : Image(0, 0, 0, nullptr) {}
9
10 Image::Image(unsigned M, unsigned N, unsigned Q) : Image(M, N, Q, new
    ↪ Image::pixelT[M * N]) {}
11
12 Image::Image(const Image& oldImage) : Image(oldImage.M, oldImage.N, oldImage.Q) {
13     for (unsigned i = 0; i < M * N; i++) { pixelValue[i] = oldImage.pixelValue[i]; }
14 }
15
16 // Move constructor - take old image's pixel values and make old image invalid
17 Image::Image(Image&& oldImage) : Image(oldImage.M, oldImage.N, oldImage.Q,
    ↪ oldImage.pixelValue) {
18     oldImage.M = oldImage.N = oldImage.Q = 0;
19     oldImage.pixelValue = nullptr;
20 }
21
22 Image::Image(unsigned M, unsigned N, unsigned Q, pixelT* pixels)
23     : M(M), N(N), Q(Q), pixelValue(pixels) {}
24
25 Image::~Image() {

```

```

26     if (pixelValue != nullptr) { delete[] pixelValue; }
27 }
28
29 // Slightly modified version of readImage() function provided by Dr. Bebis
30 Image Image::read(std::istream& in) {
31     int N, M, Q;
32     unsigned char* charImage;
33     char header[100], *ptr;
34
35     static_assert(sizeof(Image::pixelT) == 1,
36         "Image reading only supported for single-byte pixel types.");
37
38     // read header
39     in.getline(header, 100, '\n');
40     if ((header[0] != 'P') || (header[1] != '5')) { throw std::runtime_error("Image
41         ↪ is not PGM!"); }
42
43     in.getline(header, 100, '\n');
44     while (header[0] == '#') in.getline(header, 100, '\n');
45
46     N = strtol(header, &ptr, 0);
47     M = atoi(ptr);
48
49     in.getline(header, 100, '\n');
50     Q = strtol(header, &ptr, 0);
51
52     if (Q > 255) throw std::runtime_error("Image cannot be read correctly (Q >
53         ↪ 255)!");
54
55     charImage = new unsigned char[M * N];
56
57     in.read(reinterpret_cast<char*>(charImage), (M * N) * sizeof(unsigned char));
58
59     if (in.fail()) throw std::runtime_error("Image has wrong size!");
60
61     return Image(M, N, Q, charImage);
62 }
63
64 // Slightly modified version of writeImage() function provided by Dr. Bebis
65 std::ostream& operator<<(std::ostream& out, const Image& im) {
66     static_assert(sizeof(Image::pixelT) == 1,
67         "Image writing only supported for single-byte pixel types.");
68
69     out << "P5" << std::endl;
70     out << im.N << " " << im.M << std::endl;
71     out << im.Q << std::endl;
72
73     out.write(reinterpret_cast<char*>(im.pixelValue), (im.M * im.N) *
74         ↪ sizeof(unsigned char));
75
76     if (out.fail()) throw std::runtime_error("Something failed with writing
77         ↪ image.");
78 }

```

```

75
76 Image& Image::operator=(const Image& rhs) {
77     if (pixelValue != nullptr) delete[] pixelValue;
78
79     M = rhs.M;
80     N = rhs.N;
81     Q = rhs.Q;
82
83     pixelValue = new pixelT[M * N];
84
85     for (unsigned i = 0; i < M * N; i++) pixelValue[i] = rhs.pixelValue[i];
86
87     return *this;
88 }
89
90 Image& Image::operator=(Image&& rhs) {
91     if (pixelValue != nullptr) delete[] pixelValue;
92
93     M = rhs.M;
94     N = rhs.N;
95     Q = rhs.Q;
96     pixelValue = rhs.pixelValue;
97
98     rhs.M = rhs.N = rhs.Q = 0;
99     rhs.pixelValue = nullptr;
100
101     return *this;
102 }
103
104 Image::pixelT* Image::operator[](unsigned i) {
105     return pixelValue + i * N;
106 }
107
108 const Image::pixelT* Image::operator[](unsigned i) const {
109     return pixelValue + i * N;
110 }
111
112 // Slightly modified version of readImageHeader() function provided by Dr. Bebis
113 Image::Header Image::Header::read(std::istream& in) {
114     unsigned char* charImage;
115     char header[100], *ptr;
116     Header re;
117
118     // read header
119     in.getline(header, 100, '\n');
120     if ((header[0] == 'P') && (header[1] == '5')) {
121         re.type = GRAY;
122     } else if ((header[0] == 'P') && (header[1] == '6')) {
123         re.type = COLOR;
124     } else
125         throw std::runtime_error("Image is not PGM or PPM!");
126
127     in.getline(header, 100, '\n');

```

```

128 while (header[0] == '#') in.getline(header, 100, '\n');
129
130 re.N = strtol(header, &ptr, 0);
131 re.M = atoi(ptr);
132
133 in.getline(header, 100, '\n');
134
135 re.Q = strtol(header, &ptr, 0);
136
137 return re;
138 }
139
140 std::ostream& operator<<(std::ostream& out, const Image::Header& head) {
141     switch (head.type) {
142         case Image::Header::Type::COLOR:
143             out << "PPM Color ";
144             break;
145         case Image::Header::Type::GRAY:
146             out << "PGM Grayscale ";
147     }
148     out << "Image size " << head.M << " x " << head.N << " and max value of " <<
        ↪ head.Q << ".";
149 }

```

Listing 3: Implementation file for the Histogram supporting library.

```

1 // Common/histogram_tools.cpp
2 #include "histogram_tools.h"
3
4 #include <algorithm>
5 #include <iostream>
6
7 void Histogram::print(unsigned* histogram, unsigned bins, unsigned width, unsigned
    ↪ height) {
8     // An adjusted histogram, which has been binned
9     unsigned* binnedHistogram = new unsigned[width];
10    // Maximum number of original bins represented by each new bin
11    // Each bin is this size, except maybe the last bin (which may be smaller)
12    unsigned binSize = 1 + (bins - 1) / width;
13    // The maximum number of observations in all bins
14    unsigned maxBin = 0;
15
16    // Calculate new binnedHistogram and maxBin
17    #pragma omp parallel for reduction(max : maxBin)
18    for (unsigned i = 0; i < width; i++) {
19        binnedHistogram[i] = 0;
20        for (unsigned j = binSize * i; j < binSize * (i + 1) && j < bins; j++) {
21            binnedHistogram[i] += histogram[j];
22        }
23        maxBin = std::max(binnedHistogram[i], maxBin);
24    }
25

```

```

26 // The maximum number of observations each tick can represent
27 // May represent as few as 1, if present on the top of a histogram bar
28 unsigned tickSize = 1 + (maxBin - 1) / height;
29
30 for (unsigned i = 1; i <= height; i++) {
31     unsigned threshold = (height - i) * tickSize;
32     for (unsigned j = 0; j < width; j++) {
33         if (binnedHistogram[j] > threshold)
34             std::cout << '*';
35         else
36             std::cout << ' ';
37     }
38     std::cout << '\n';
39 }
40
41 delete[] binnedHistogram;
42 }

```

Listing 4: Implementation file for the sample program.

```

1  #include <iostream>
2  #include <fstream>
3  #include <sstream>
4
5  #include "../Common/image.h"
6
7  /*
8   Subsamples and image based on the sampling factor
9   @Param: image - the input image that will be sampled
10  @Param: subsample_factor - the factor by which to sample
11  @Return: void
12  */
13 void subsample_image(Image& image, int subsample_factor){
14
15     //Todo: add option to not resize image
16     //int M = image.rows / subsample_factor;
17     //int N = image.cols / subsample_factor;
18     //int Q = image.maxVal;
19     //pixelT* pixels;
20
21     //Image newImage = Image(M, N, Q, image.pixels);
22
23     // iterate through image to get the sample
24     for(int i=0; i<image.cols; i += subsample_factor){
25         for(int j=0; j<image.rows; j += subsample_factor) {
26
27             // save the sampled pixel
28             int pixelSample = image[i][j];
29
30             // Modify neighbor pixels to match the sampled pixel
31             for (int k = 0; k < subsample_factor; k++)
32                 {

```

```

33         for (int l = 0; l < subsample_factor; l++)
34         {
35             image[i + k][j + l] = pixelSample;
36         }
37     }
38 }
39 }
40 }
41
42 int main(int argc, char** argv) {
43
44     int M, N, Q;
45     bool type;
46     int val;
47     int subsample_factor;
48     std::istringstream ss(argv[3]);
49
50     if(ss >> subsample_factor) {
51         if(256 % subsample_factor != 0 || subsample_factor > 256){
52             std::cout << "Error: Subsample factor should be power of 2 less than 256"
53                 << std::endl;
54             return 1;
55         }
56     }
57
58     std::ifstream inFile(argv[1]);
59
60     Image image = Image::read(inFile);
61
62     std::cout << "Question 1: Sampling." << std::endl;
63
64     subsample_image(image, subsample_factor);
65
66     // Save output image
67     std::ofstream outFile;
68     outFile.open(argv[2]);
69     outFile << image;
70     outFile.close();
71
72     return 0;
73 }

```

Listing 5: Implementation file for the quantize program.

```

1  #include <iostream>
2  #include <fstream>
3  #include <sstream>
4  #include <vector>
5
6  #include "../Common/image.h"
7

```

```

8  /*
9  Quantizes an image based on the quantization level
10 @Param: image - the input image that will be quantized
11 @Param: quantization_level - the number of gray level values to use
12 @Return: void
13 */
14 void quantize_image(Image& image, int quantization_level){
15
16     int offset = 256 / quantization_level;
17     std::vector<int> newPixelValues;
18
19     // calculate new values for pixels
20     for (int i = 0; i < quantization_level; i++)
21         newPixelValues.push_back(i * offset);
22
23
24     for(int i=0; i<image.cols; i++) {
25         for(int j=0; j<image.rows; j++) {
26
27             // current pixel
28             int pixelValue = image[i][j];
29
30             // index for new pixel value
31             int index = pixelValue / offset;
32
33             // update image pixel
34             image[i][j] = newPixelValues[index];
35         }
36     }
37 }
38
39 int main(int argc, char** argv) {
40     int M, N, Q;
41     bool type;
42     int val;
43     int quantization_level;
44     std::istringstream ss(argv[3]);
45
46     if(ss >> quantization_level) {
47         if(quantization_level > 256){
48             std::cout << "Error: Quantization level should be less than 256" <<
49                 ↵ std::endl;
50             return 1;
51         }
52     }
53
54     std::ifstream inFile(argv[1]);
55
56     Image image = Image::read(inFile);
57
58     std::cout << "Question 2: Quantization." << std::endl;
59

```



```

60     quantize_image(image, quantization_level);
61
62     // Save output image
63     std::ofstream outFile;
64     outFile.open(argv[2]);
65     outFile << image;
66     outFile.close();
67
68     return 0;
69 }

```

Listing 6: Implementation file for the equalize program.

```

1  // Q3-Equalization/main.cpp
2  #include <cstring>
3  #include <fstream>
4  #include <iostream>
5  #include <map>
6  #include <mutex>
7
8  #include "../Common/histogram_tools.h"
9  #include "../Common/image.h"
10
11 // Struct for inputting arguments from command line
12 struct Arguments {
13     char *inputImagePath, *outImagePath;
14     Image inputImage;
15     std::ofstream outFile;
16     unsigned histogramWidth = 64, histogramHeight = 10;
17     bool plot = false;
18     std::ofstream plotFile;
19 };
20
21 void equalize(Arguments& arg);
22 bool verifyArguments(int argc, char** argv, Arguments& arg, int& err);
23 void printHelp();
24
25 int main(int argc, char** argv) {
26     int err;
27     Arguments arg;
28
29     if (!verifyArguments(argc, argv, arg, err)) { return err; }
30
31     equalize(arg);
32
33     return 0;
34 }
35
36 void equalize(Arguments& arg) {
37     unsigned* histogram = new unsigned[arg.inputImage.maxVal + 1];
38     unsigned* newHistogram = new unsigned[arg.inputImage.maxVal + 1];
39     unsigned* cdf = new unsigned[arg.inputImage.maxVal + 1];

```

```

40     std::mutex* locks      = new std::mutex[arg.inputImage.maxVal + 1];
41     // Initialise histogram bins to be empty
42     #pragma omp parallel for
43     for (unsigned i = 0; i <= arg.inputImage.maxVal; i++) {
44         histogram[i] = newHistogram[i] = 0;
45     }
46
47     // Create histogram
48     #pragma omp parallel for
49     for (unsigned i = 0; i < arg.inputImage.rows * arg.inputImage.cols; i++) {
50         unsigned bin = arg.inputImage.pixels[i];
51         locks[bin].lock();
52         histogram[bin]++;
53         locks[bin].unlock();
54     }
55
56     // Calculate CDF
57     cdf[0] = histogram[0];
58     for (unsigned i = 1; i <= arg.inputImage.maxVal; i++) {
59         cdf[i] = cdf[i - 1] + histogram[i];
60     }
61
62     // Transform image with the CDF
63     #pragma omp parallel for
64     for (unsigned i = 0; i < arg.inputImage.rows * arg.inputImage.cols; i++) {
65         Image::pixelT& pixelVal = arg.inputImage.pixels[i];
66         pixelVal
67             = cdf[pixelVal] * arg.inputImage.maxVal /
68               (arg.inputImage.rows * arg.inputImage.cols);
69     }
70
71     // Write new transformed image out
72     arg.outFile << arg.inputImage;
73     arg.outFile.close();
74
75     // Calculate histogram of new image
76     #pragma omp parallel for
77     for (unsigned i = 0; i < arg.inputImage.rows * arg.inputImage.cols; i++) {
78         unsigned bin = arg.inputImage.pixels[i];
79         locks[bin].lock();
80         newHistogram[bin]++;
81         locks[bin].unlock();
82     }
83
84     // Print histograms
85     std::cout << "\nHistogram of input image \"" << arg.inputImagePath << "":\n";
86     Histogram::print(histogram, arg.inputImage.maxVal + 1, arg.histogramWidth,
87                      arg.histogramHeight);
88
89     std::cout << "\nHistogram of output image \"" << arg.outImagePath << "":\n";
90     Histogram::print(newHistogram, arg.inputImage.maxVal + 1, arg.histogramWidth,
91                      arg.histogramHeight);
92
93     // Print histogram data for plot file

```

```

93     if (arg.plot) {
94         arg.plotFile << "Image Input Equalized\n";
95         for (unsigned i = 0; i <= arg.inputImage.maxVal; i++) {
96             arg.plotFile << i << "    " << histogram[i] << "    " << newHistogram[i]
97                 << '\n';
98         }
99         arg.plotFile.close();
100     }
101
102     delete[] histogram;
103     delete[] newHistogram;
104     delete[] cdf;
105     delete[] locks;
106 }
107
108 bool verifyArguments(int argc, char** argv, Arguments& arg, int& err) {
109     // If there are not the minimum number of arguments, print help and leave
110     if (argc < 2 ||
111         (argc < 3 && strcmp(argv[1], "-h") && strcmp(argv[1], "--help"))) {
112         std::cout << "Missing operand.\n";
113         err = 1;
114         printHelp();
115         return false;
116     }
117
118     // If the user asks for the help menu, print help and leave
119     if (!strcmp(argv[1], "-h") || !strcmp(argv[1], "--help")) {
120         printHelp();
121         return false;
122     }
123
124     // Find optional argument switches
125     for (unsigned i = 3; i < argc; i++) {
126         if (!strcmp(argv[i], "-width")) {
127             if (i + 1 >= argc) {
128                 std::cout << "Missing width";
129                 err = 1;
130                 printHelp();
131                 return false;
132             }
133
134             arg.histogramWidth = strtoul(argv[i + 1], nullptr, 10);
135             if (arg.histogramWidth == 0) {
136                 std::cout << "Width \"< " << argv[i + 1]
137                     << "\" could not be recognised as a positive integer.";
138                 err = 2;
139                 return false;
140             }
141
142             i++;
143         } else if (!strcmp(argv[i], "-height")) {
144             if (i + 1 >= argc) {
145                 std::cout << "Missing height";

```

```

146     err = 1;
147     break;
148 }
149
150 arg.histogramHeight = strtoul(argv[i + 1], nullptr, 10);
151 if (arg.histogramHeight == 0) {
152     std::cout << "Height \"" << argv[i + 1]
153         << "\" could not be recognised as a positive integer.";
154     err = 2;
155     return false;
156 }
157
158 i++;
159 } else if (!strcmp(argv[i], "-p")) {
160     if (i + 1 >= argc) {
161         std::cout << "Missing plot output file";
162         err = 1;
163         break;
164     }
165
166     arg.plot = true;
167     arg.plotFile.open(argv[i + 1]);
168
169     if (!arg.plotFile) {
170         std::cout << "Plot file \"" << argv[i + 1]
171             << "\" could not be opened";
172         err = 2;
173         return false;
174     }
175
176     i++;
177 }
178 }
179
180 // Required arguments
181 arg.inputImagePath = argv[1];
182 std::ifstream inFile(argv[1]);
183 try {
184     arg.inputImage = Image::read(inFile);
185 } catch (std::exception& e) {
186     std::cout << "Image \"" << argv[1] << "\" failed to be read: \"" << e.what()
187         << "\"\n";
188     err = 2;
189     return false;
190 }
191
192 arg.outImagePath = argv[2];
193 arg.outFile.open(argv[2]);
194 if (!arg.outFile) {
195     std::cout << "Could not open \"" << argv[2] << "\"\n";
196     err = 2;
197     return false;
198 }

```

```

199     return true;
200 }
201
202
203 void printHelp() {
204     std::cout
205         << "Usage: equalize <image> <output> [options]    (1)\n"
206         << "    or: equalize -h                                (2)\n\n"
207         << "(1) Take an image file as input, equalize its histogram,\n"
208         << "    and write new image to output file. Displays the original\n"
209         << "    histogram and the new equalized histogram.\n"
210         << "(2) Print this help menu\n\n"
211         << "Options:\n"
212         << "  -width <width>      Number of visual histogram bins\n"
213         << "  -height <height>   Height of visual histogram (in lines)\n"
214         << "  -p <file>          Send histogram plotting data to a file for\n"
215         << "    ↪ gnuplot\n";
216 }

```

Listing 7: Implementation file for the specify program.

```

1  // Q4-Specification/main.cpp
2  #include <cstring>
3  #include <fstream>
4  #include <iostream>
5  #include <mutex>
6  #include <regex>
7  #include <vector>
8
9  #include "../Common/histogram_tools.h"
10 #include "../Common/image.h"
11
12 // Struct for inputting arguments from command line
13 struct Arguments {
14     char *inputImagePath, *outImagePath, *histogramPath;
15     Image inputImage;
16     std::ifstream histogramFile;
17     std::ofstream outFile;
18     unsigned histogramWidth = 64, histogramHeight = 10;
19     bool plot = false;
20     std::ofstream plotFile;
21 };
22
23 int specify(Arguments& arg);
24 void printHistogram(unsigned* histogram, const Arguments& arg);
25 bool verifyArguments(int argc, char** argv, Arguments& arg, int& err);
26 void printHelp();
27
28 int main(int argc, char** argv) {
29     int err;
30     Arguments arg;
31

```

```

32     if (!verifyArguments(argc, argv, arg, err)) { return err; }
33
34     return specify(arg);
35 }
36
37 int specify(Arguments& arg) {
38     unsigned* histogram      = new unsigned[arg.inputImage.maxVal + 1];
39     unsigned* newHistogram   = new unsigned[arg.inputImage.maxVal + 1];
40     unsigned* cdf            = new unsigned[arg.inputImage.maxVal + 1];
41     std::mutex* locks        = new std::mutex[arg.inputImage.maxVal + 1];
42     std::vector<unsigned> targetHistogram;
43     unsigned targetPixels = 0; // Number of pixels in the target histogram
44
45     // Initialise histogram bins to be empty
46     #pragma omp parallel for
47     for (unsigned i = 0; i <= arg.inputImage.maxVal; i++) {
48         histogram[i] = newHistogram[i] = 0;
49     }
50
51     // Create input image histogram
52     #pragma omp parallel for
53     for (unsigned i = 0; i < arg.inputImage.rows * arg.inputImage.cols; i++) {
54         unsigned bin = arg.inputImage.pixels[i];
55         locks[bin].lock();
56         histogram[bin]++;
57         locks[bin].unlock();
58     }
59
60     // Start with enough space to hold our input image. If we need more, we can get
61     // more, but we're probably working with similarly-valued images.
62     targetHistogram.reserve(arg.inputImage.maxVal + 1);
63
64     // Read in target histogram
65     std::string line;
66     std::regex rHistogram("^([[:digit:]]+)[[:space:]]+([[:digit:]]+).*");
67     std::smatch matches;
68     while (arg.histogramFile) {
69         std::getline(arg.histogramFile, line);
70         if (!std::regex_match(line, matches, rHistogram)) continue;
71
72         if (stoul(matches[1].str()) != targetHistogram.size()) {
73             std::cout << "Error in reading histogram file \"" << arg.histogramPath
74                 << ":\n"
75                 << "Bucket \"" << stoul(matches[1].str())
76                 << "\" was expected to be \"" << targetHistogram.size()
77                 << "\".";
78         }
79
80         targetHistogram.push_back(stoul(matches[2].str()));
81         targetPixels += targetHistogram.back();
82     }
83     arg.histogramFile.close();
84

```

```

85 // Calculate CDFs
86 std::vector<unsigned> targetCDF(targetHistogram.size());
87 cdf[0] = histogram[0];
88 targetCDF[0] = targetHistogram[0];
89
90 for (unsigned i = 1; i <= arg.inputImage.maxVal; i++) {
91     cdf[i] = cdf[i - 1] + histogram[i];
92 }
93 for (unsigned i = 1; i < targetHistogram.size(); i++) {
94     targetCDF[i] = targetCDF[i - 1] + targetHistogram[i];
95 }
96
97 // Transform input image with its CDF and inverse CDF of target histogram
98 #pragma region CDF transformation
99 // Separate cases for if the images have different dimensions/maxVal, to make
100 // calculation easier
101 if (arg.inputImage.maxVal == targetHistogram.size() - 1) {
102     if (arg.inputImage.rows * arg.inputImage.cols == targetPixels) {
103 #pragma omp parallel for
104         for (unsigned i = 0; i < arg.inputImage.rows * arg.inputImage.cols; i++) {
105             Image::pixelT& pixelVal = arg.inputImage.pixels[i];
106
107             unsigned inversePixel = cdf[pixelVal];
108
109             pixelVal = targetCDF.rend() -
110                 std::lower_bound(targetCDF.rbegin(), targetCDF.rend(),
111                     inversePixel, std::greater<unsigned>());
112         }
113     } else {
114 #pragma omp parallel for
115         for (unsigned i = 0; i < arg.inputImage.rows * arg.inputImage.cols; i++) {
116             Image::pixelT& pixelVal = arg.inputImage.pixels[i];
117
118             unsigned inversePixel = cdf[pixelVal] * targetPixels /
119                 (arg.inputImage.rows * arg.inputImage.cols);
120             pixelVal = targetCDF.rend() -
121                 std::lower_bound(targetCDF.rbegin(), targetCDF.rend(),
122                     inversePixel, std::greater<unsigned>());
123         }
124     }
125 } else if (arg.inputImage.rows * arg.inputImage.cols == targetPixels) {
126 #pragma omp parallel for
127     for (unsigned i = 0; i < arg.inputImage.rows * arg.inputImage.cols; i++) {
128         Image::pixelT& pixelVal = arg.inputImage.pixels[i];
129
130         unsigned inversePixel =
131             cdf[pixelVal] * arg.inputImage.maxVal / (targetHistogram.size() - 1);
132         pixelVal = targetCDF.rend() -
133             std::lower_bound(targetCDF.rbegin(), targetCDF.rend(),
134                 inversePixel, std::greater<unsigned>());
135     }
136 } else {
137     // In this case, we need to do math with ull because of the multiplications

```

```

138 // overflowing The result after division should fit within an unsigned, though
139 #pragma omp parallel for
140 for (unsigned i = 0; i < arg.inputImage.rows * arg.inputImage.cols; i++) {
141     Image::pixelT& pixelVal = arg.inputImage.pixels[i];
142
143     unsigned inversePixel = ((unsigned long long) cdf[pixelVal]) *
144                             arg.inputImage.maxVal * targetPixels /
145                             (arg.inputImage.rows * arg.inputImage.cols *
146                             (targetHistogram.size() - 1));
147     pixelVal = targetCDF.rend() -
148                 std::lower_bound(targetCDF.rbegin(), targetCDF.rend(),
149                                 inversePixel, std::greater<unsigned>());
150 }
151 }
152 #pragma endregion CDF transformation
153
154 // Write new transformed image out
155 arg.outFile << arg.inputImage;
156 arg.outFile.close();
157
158 // Calculate histogram of new image
159 #pragma omp parallel for
160 for (unsigned i = 0; i < arg.inputImage.rows * arg.inputImage.cols; i++) {
161     unsigned bin = arg.inputImage.pixels[i];
162     locks[bin].lock();
163     newHistogram[bin]++;
164     locks[bin].unlock();
165 }
166
167 // Print histograms
168 std::cout << "\nHistogram of input image \"" << arg.inputImagePath << "":\n";
169 Histogram::print(histogram, arg.inputImage.maxVal + 1, arg.histogramWidth,
170                 arg.histogramHeight);
171
172 std::cout << "\nInput histogram \"" << arg.histogramPath << "":\n";
173 Histogram::print(&targetHistogram.front(), targetHistogram.size(),
174                 arg.histogramWidth, arg.histogramHeight);
175
176 std::cout << "\nHistogram of output image \"" << arg.outImagePath << "":\n";
177 Histogram::print(newHistogram, arg.inputImage.maxVal + 1, arg.histogramWidth,
178                 arg.histogramHeight);
179
180 // Print histogram data for plot file
181 if (arg.plot) {
182     arg.plotFile << "Source Input-Image Input-Histogram Specified\n";
183     unsigned i;
184     for (i = 0; i <= arg.inputImage.maxVal && i < targetHistogram.size(); i++) {
185         arg.plotFile << i << "    " << histogram[i] << "    "
186                     << targetHistogram[i] << "    " << newHistogram[i] << '\n';
187     }
188     arg.plotFile.close();
189 }
190

```



```

191     delete[] histogram;
192     delete[] newHistogram;
193     delete[] cdf;
194     delete[] locks;
195
196     return 0;
197 }
198
199 bool verifyArguments(int argc, char** argv, Arguments& arg, int& err) {
200     if (argc < 2 ||
201         (argc < 4 && strcmp(argv[1], "-h") && strcmp(argv[1], "--help"))) {
202         std::cout << "Missing operand.\n";
203         err = 1;
204         printHelp();
205         return false;
206     }
207
208     if (!strcmp(argv[1], "-h") || !strcmp(argv[1], "--help")) {
209         printHelp();
210         return false;
211     }
212
213     // Find optional argument switches
214     for (unsigned i = 4; i < argc; i++) {
215         if (!strcmp(argv[i], "-width")) {
216             if (i + 1 >= argc) {
217                 std::cout << "Missing width";
218                 err = 1;
219                 printHelp();
220                 return false;
221             }
222
223             arg.histogramWidth = strtoul(argv[i + 1], nullptr, 10);
224             if (arg.histogramWidth == 0) {
225                 std::cout << "Width \"" << argv[i + 1]
226                     << "\" could not be recognised as a positive integer.";
227                 err = 2;
228                 return false;
229             }
230
231             i++;
232         } else if (!strcmp(argv[i], "-height")) {
233             if (i + 1 >= argc) {
234                 std::cout << "Missing height";
235                 err = 1;
236                 break;
237             }
238
239             arg.histogramHeight = strtoul(argv[i + 1], nullptr, 10);
240             if (arg.histogramHeight == 0) {
241                 std::cout << "Height \"" << argv[i + 1]
242                     << "\" could not be recognised as a positive integer.";
243                 err = 2;

```

```

244     return false;
245 }
246
247 i++;
248 } else if (!strcmp(argv[i], "-p")) {
249     if (i + 1 >= argc) {
250         std::cout << "Missing plot output file";
251         err = 1;
252         break;
253     }
254
255     arg.plot = true;
256     arg.plotFile.open(argv[i + 1]);
257
258     if (!arg.plotFile) {
259         std::cout << "Plot file \"" << argv[i + 1]
260             << "\" could not be opened";
261         err = 2;
262         return false;
263     }
264
265     i++;
266 }
267 }
268
269 // Required arguments
270 arg.inputImagePath = argv[1];
271 std::ifstream inFile(argv[1]);
272 try {
273     arg.inputImage = Image::read(inFile);
274 } catch (std::exception& e) {
275     std::cout << "Image \"" << argv[1] << "\" failed to be read: \"" << e.what()
276         << "\"\n";
277     err = 2;
278     return false;
279 }
280
281 arg.histogramPath = argv[2];
282 arg.histogramFile.open(argv[2]);
283 if (!arg.histogramFile) {
284     std::cout << "Could not open \"" << argv[2] << "\"\n";
285     err = 2;
286     return false;
287 }
288
289 arg.outImagePath = argv[3];
290 arg.outFile.open(argv[3]);
291 if (!arg.outFile) {
292     std::cout << "Could not open \"" << argv[3] << "\"\n";
293     err = 2;
294     return false;
295 }
296

```

```

297     return true;
298 }
299
300 void printHelp() {
301     std::cout
302         << "Usage: specify <image> <histogram> <output> [options]    (1)\n"
303         << "    or: specify -h                                           (2)\n\n"
304         << "(1) Take an image file as input, change its histogram to the\n"
305         << "    specified histogram, and write new image to output file.\n"
306         << "    Displays the original histogram and the new equalized histogram.\n"
307         << "    Histogram files can be obtained by running 'equalize' with\n"
308         << "    the -p flag set (or 'specify' with the -p flag set).\n"
309         << "(2) Print this help menu\n\n"
310         << "Options:\n"
311         << "  -width <width>      Number of visual histogram bins\n"
312         << "  -height <height>   Height of visual histogram (in lines)\n"
313         << "  -p <file>          Send histogram plotting data to a file for\n"
314         << "                    ↪ gnuplot\n";
315 }

```

Listing 8: gnuplot plotting file for generating two-histogram comparison plots.  
Used for generating comparison plots in section 3.3.

```

1  # Q3-Equalization/plot-histograms.plt
2  # A gnuplot plotting file to plot the two histograms of data from equalize with
   ↪ the -p switch
3  if (!exists("outfile")) outfile='plot.eps'
4
5  if (!exists("imageName")) {
6      set title "Comparison of histograms of input and output (equalized) images"
7  } else {
8      set title "Comparison of histograms of " . imageName . " and equalized image"
   ↪ noenhanced
9  }
10
11 set terminal postscript eps enhanced color size 6,3
12 set output outfile
13 set style data histogram
14 set style histogram cluster gap 1
15 set style fill solid
16 set boxwidth 0.9
17
18 unset xtics
19
20 # Colors chosen using ColorBrewer 2.0 qualitative scheme "Dark2"
21 # https://colorbrewer2.org/#type=qualitative&scheme=Dark2&n=3
22 plot infile using 2:xtic(1) ti col linecolor rgb "#1b9e77",\
23     '' u 3 ti col linecolor rgb "#d95f02"

```

Listing 9: gnuplot plotting file for generating three-histogram comparison plots.  
Used for generating comparison plots in section 4.3.

```

1  # Q4-Specification/plot-histograms.plt
2  # A gnuplot plotting file to plot the three histograms of data from specify with
   ↪ the -p switch
3  if (!exists("outfile")) outfile='plot.eps'
4
5  if (!exists("imageName") || !exists("histoName")) {
6      set title "Comparison of histograms of input image, input histogram, and output
   ↪ image"
7  } else {
8      set title "Comparison of histograms of " . imageName . ", " . histoName . ", and
   ↪ specified image" noenhanced
9  }
10
11 set terminal postscript eps enhanced color size 6,3
12 set output outfile
13 set style data histogram
14 set style histogram cluster gap 1
15 set style fill solid
16 set boxwidth 0.9
17
18 unset xtics
19
20 # Colors chosen using ColorBrewer 2.0 qualitative scheme "Dark2"
21 # https://colorbrewer2.org/#type=qualitative&scheme=Dark2&n=3
22 plot infile using 2:xtic(1) ti imageName noenhanced linecolor rgb "#1b9e77",\
23     '' u 3 ti histoName noenhanced linecolor rgb "#d95f02",\
24     '' u 4 ti col linecolor rgb "#7570b3"

```