ECE 5273
HW 5 Solution

Spring 2024 Dr. Havlicek

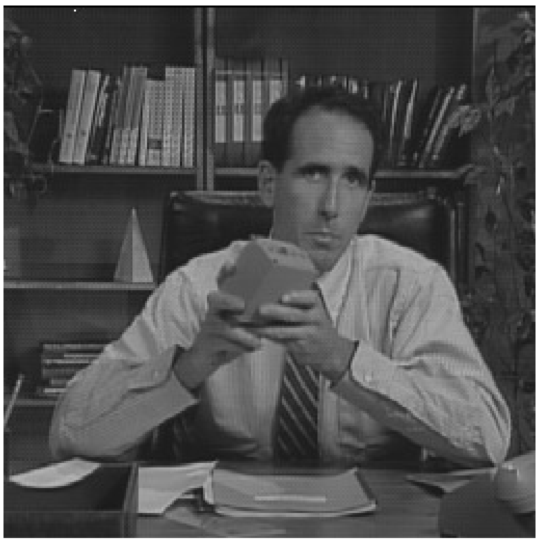
Note: This document contains solutions in both Matlab and traditional C.

Matlab Solution:

1.

(a)

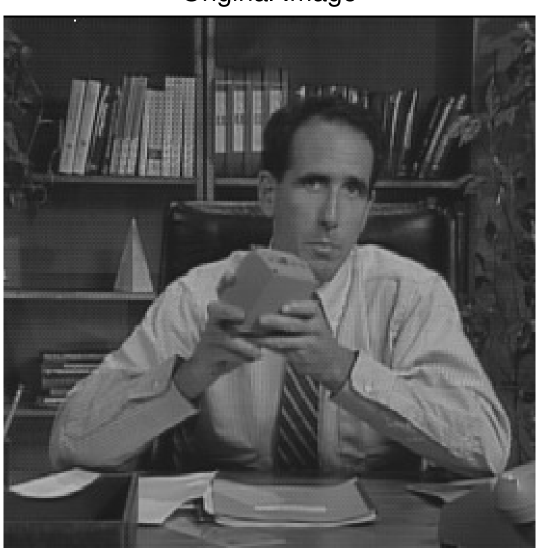
Original Image



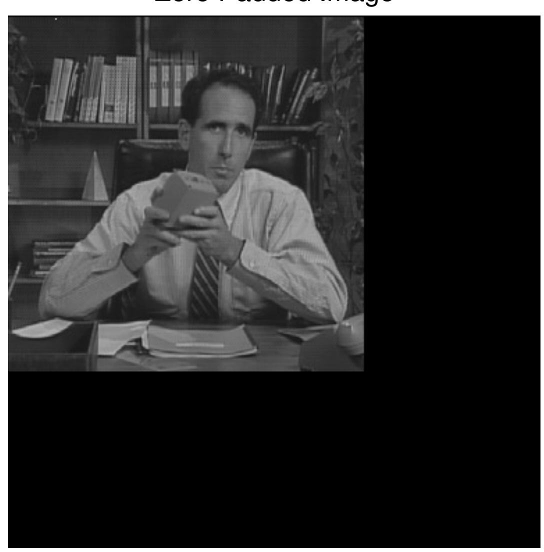
Filtered Image

(b)

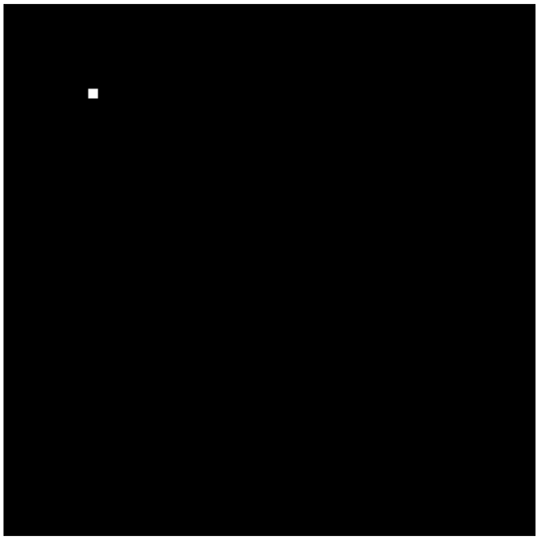
Original Image



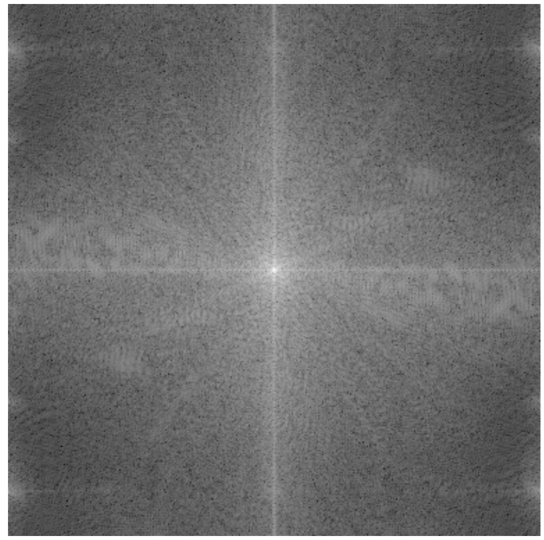
Zero Padded Image



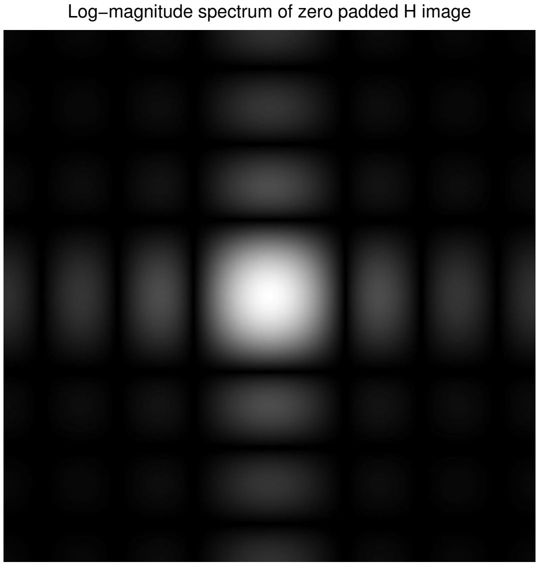
Zero Padded Impulse Resp



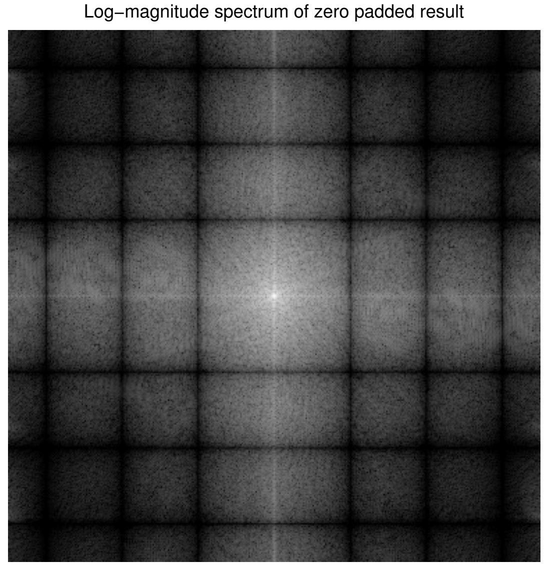
Log−magnitude spectrum of zero padded image



Log−magnitude spectrum of zero padded H image



Log−magnitude spectrum of zero padded result



Zero Padded Result

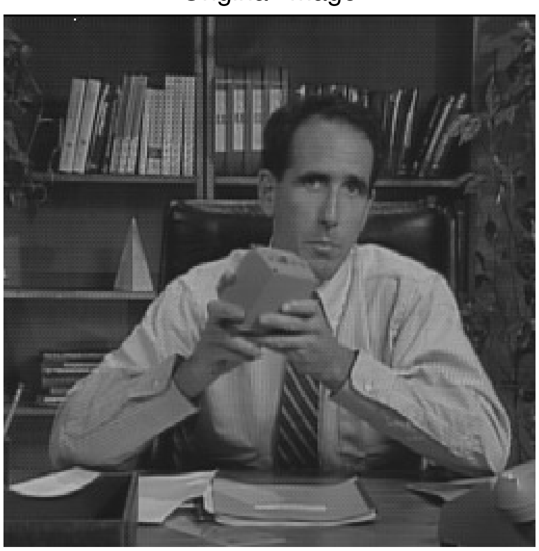
Final Filtered Image

Matlab command window output:

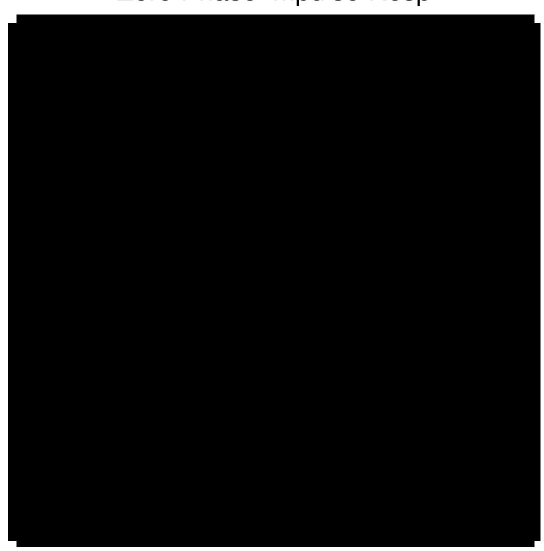
```
(b): max difference from part (a): 0
```

(c)

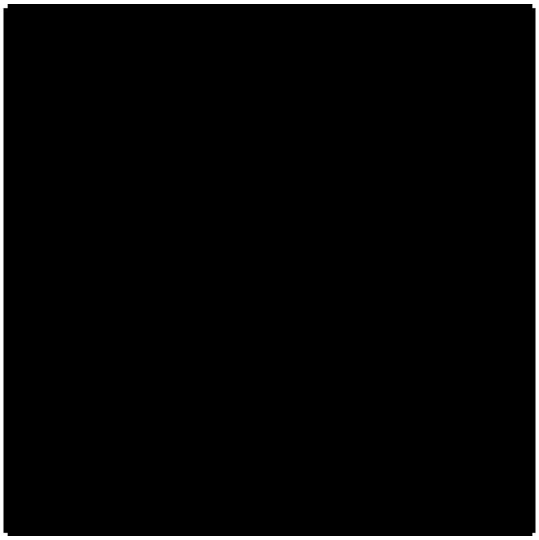
Original Image



Zero Phase Impulse Resp



Zero Padded zero−phase H



Final Filtered Image

Matlab command window output:

```
(c): max difference from part (a): 0
```

Matlab m-file listing:

```
%
% P1.m
%
% 04/05/2015 jph
%


%----------------------------------------------------------------------
%
% P1(a): apply a 7x7 average filter to salesman image by doing linear
% convolution in the image domain.
%
% Handle edge effects by zero padding.
%

X = ReadBin('salesman.bin',256);
figure(1);image(X);colormap(gray(256));axis('image','off');
title('Original Image','FontSize',18);
print -deps Msalesman.eps;

X2 = zeros(262,262);
X2(4:259,4:259) = X;
Y2 = zeros(262,262);

for row=4:259
  for col=4:259
```

```
    Y2(row,col) = sum(sum(X2(row-3:row+3,col-3:col+3)))/49;
  end
end

Y = stretch(Y2(4:259,4:259));
figure(2);image(Y);colormap(gray(256));axis('image','off');
title('Filtered Image','FontSize',18);
print -deps MY1a.eps;

% Save the result image for comparison with later results
Y1a = Y;


%----------------------------------------------------------------------
%
% P1(b): Use the method of Example 3 on page 5.61 of the Notes to do
% the same linear convolution by pointwise multiplication of DFT's.
%
% The impulse response image H will be 128x128.
%
% The original image is already in the Matlab array X.
%

% Make the 128x128 impulse response image
H = zeros(128,128);
H(62:68,62:68) = 1/49;

% Zero pad the original image and the H image
Padsize = 256 + 128 - 1;
ZPX = zeros(Padsize,Padsize);
ZPX(1:256,1:256) = X;
figure(3);image(ZPX);colormap(gray(256));axis('image','off');
title('Zero Padded Image','FontSize',18);
print -deps MZPX1b.eps;

ZPH = zeros(Padsize,Padsize);
ZPH(1:128,1:128) = H;
figure(4);image(stretch(ZPH));colormap(gray(256));axis('image','off');
title('Zero Padded Impulse Resp','FontSize',18);
print -deps MZPH1b.eps;

% Compute DFT's of zero padded images
ZPXtilde = fft2(ZPX);
ZPHtilde = fft2(ZPH);

% Show centered log-magnitude spectra
ZPXtildeDisplay = stretch(log(1 + abs(fftshift(ZPXtilde))));
figure(5);image(ZPXtildeDisplay);colormap(gray(256));axis('image','off');
title('Log-magnitude spectrum of zero padded image','FontSize',12);
```

```
print -deps MZPXtilde1b.eps;
ZPHtildeDisplay = stretch(log(1 + abs(fftshift(ZPHtilde))));
figure(6);image(ZPHtildeDisplay);colormap(gray(256));axis('image','off');
title('Log-magnitude spectrum of zero padded H image','FontSize',12);
print -deps MZPHtilde1b.eps;

% Compute the convolution by pointwise multiplication of DFT's.
% Show the resulting zero padded image and it's centered log-magnitude
% spectrum.
ZPYtilde = ZPXtilde .* ZPHtilde;
ZPY = ifft2(ZPYtilde);

ZPYtildeDisplay = stretch(log(1 + abs(fftshift(ZPYtilde))));
figure(7);image(ZPYtildeDisplay);colormap(gray(256));axis('image','off');
title('Log-magnitude spectrum of zero padded result','FontSize',12);
print -deps MZPYtilde1b.eps;
figure(8);image(stretch(ZPY));colormap(gray(256));axis('image','off');
title('Zero Padded Result','FontSize',18);
print -deps MZPY1b.eps;

% Extract the final result image and display
Y = stretch(ZPY(65:320,65:320));
figure(9);image(Y);colormap(gray(256));axis('image','off');
title('Final Filtered Image','FontSize',18);
print -deps MY1b.eps;

% Compare this result image with the one from part (a)
disp(['(b): max difference from part (a): ' num2str(max(max(abs(Y-Y1a))))])


%----------------------------------------------------------------------
%
% P1(c): Use the method of Example 5 on page 5.76 of the Notes to do
% the same linear convolution again by pointwise multiplication of
% DFT's, this time using a 256x256 true zero-phase impulse response.
%
% The impulse response image H will be 256x256.
%
% The original image is still in the Matlab array X.
%

% Make the 256x256 impulse response image H
% Put the "square" in the center
H = zeros(256,256);
H(126:132,126:132) = 1/49;

% Now use fftshift to get the true zero-phase impulse response image
H2 = fftshift(H);
figure(10);image(stretch(H2));colormap(gray(256));axis('image','off');
```

```
title('Zero Phase Impulse Resp','FontSize',18);
print -deps MH1c.eps;

% Zero pad the input image
ZPX = zeros(512,512);
ZPX(1:256,1:256) = X;

% Make the zero padded impulse response image as in Example 5
% on page 5.76 of the notes
ZPH2 = zeros(256,256);
ZPH2(1:128,1:128) = H2(1:128,1:128);
ZPH2(1:128,385:512) = H2(1:128,129:256);
ZPH2(385:512,1:128) = H2(129:256,1:128);
ZPH2(385:512,385:512) = H2(129:256,129:256);
figure(11);image(stretch(ZPH2));colormap(gray(256));axis('image','off');
title('Zero Padded zero-phase H','FontSize',18);
print -deps MZPH1c.eps;

% Compute the filtered result by pointwise multiplication of DFT's
Y = ifft2(fft2(ZPX) .* fft2(ZPH2));
Y = stretch(Y(1:256,1:256));
figure(12);image(Y);colormap(gray(256));axis('image','off');
title('Final Filtered Image','FontSize',18);
print -deps MY1c.eps;

% Compare this result image with the one from part (a)
disp(['(c): max difference from part (a): ' num2str(max(max(abs(Y-Y1a))))])
```

```
%
% ReadBin.m
%
%   Read a square raw BYTE image (one byte per pixel, no header) from disk
%   into a matlab array.
%
%   Usage:
%   >> x = ReadBin(fn,xsize);
%
%   Input parameters:
%     fn          input filename
%     xsize       number of rows/cols in the image
%
%   Output parameters:
%     x           double output array, holds the image
%
% 4/3/03 jph
%

function [x] = ReadBin(fn,xsize)

%
% Open the file
%
fid = fopen(fn,'r');
if (fid == -1)
  error(['Could not open ',fn]);
end;

%
% Read and close the file
%
[x,Nread] = fread(fid,[xsize,xsize],'uchar');
if (Nread ~= xsize*xsize)
  error(['Complete read of ',fn,' did not succeed.']);
end;
fclose(fid);

%
% Transpose data for matlab's 'row major' convention and return
%
x = x';
```

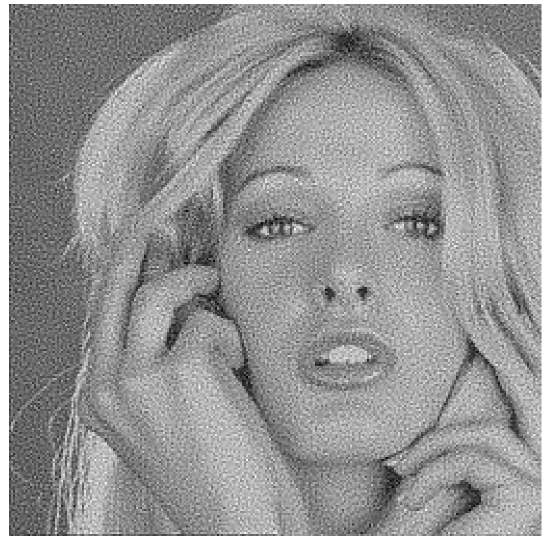
```
%
% stretch.m
%
%   Perform a full-scale contrast stretch on a byte-per-pixel gray
%   scale image.
%
%   Usage:
%   >> y = stretch(x);
%
%   Input parameters:
%     x          double array, holds the input image
%
%   Output parameters:
%     y          double array, holds the output image
%
% 4/3/03 jph
%

function [y] = stretch(x)

%
% Find the extremes and compute the scale factor
%
xMax = max(max(x));
xMin = min(min(x));
ScaleFactor = 255.0 / (xMax - xMin);

%
% Do the full-scale stretch
%
y = round((x - xMin) * ScaleFactor);
```

2.

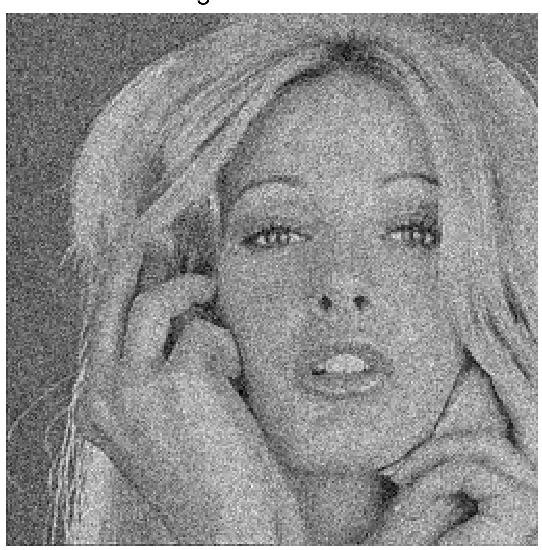
(a)

Original Tiffany Image

girl2Noise32Hi



girl2Noise32



Matlab command window output:

```
MSE girl2Noise32Hi.bin:  692.505
MSE girl2Noise32.bin:    744.4679
```

(b)

LPF on girl2

LPF on Noise32Hi

LPF on Noise32

Matlab command window output:

```
MSE:  ideal LPF on girl2:      127.7481
MSE:  ideal LPF on Noise32Hi:  398.9978
ISNR: ideal LPF on Noise32Hi:  2.3945 dB
MSE:  ideal LPF on Noise32:    550.8787
ISNR: ideal LPF on Noise32:    1.3079 dB
```

(c)

Gauss1 on girl2

Gauss1 on Noise32Hi

Gauss1 on Noise32

Matlab command window output:

```
MSE:  Gaussian LPF on girl2:     91.2585
MSE:  Gaussian LPF on Noise32Hi: 415.8219
ISNR: Gaussian LPF on Noise32Hi: 2.2152 dB
MSE:  Gaussian LPF on Noise32:   534.7741
ISNR: Gaussian LPF on Noise32:   1.4368 dB
```

(d)

Matlab command window output:

```
MSE:  Gaussian2 LPF on girl2:     60.6184
MSE:  Gaussian2 LPF on Noise32Hi: 406.7896
ISNR: Gaussian2 LPF on Noise32Hi: 2.3105 dB
MSE:  Gaussian2 LPF on Noise32:   527.771
ISNR: Gaussian2 LPF on Noise32:   1.494 dB
```

Matlab m-file listing:

```
%
% P2.m
%
% 04/05/2015 jph
%

% original girl2 image (aka tiffany)
X = ReadBin('girl2.bin',256);

% with broadband noise
XN = ReadBin('girl2Noise32.bin',256);

% with hi pass noise
XNhi = ReadBin('girl2Noise32Hi.bin',256);


%----------------------------------------------------------------------
%
% P2(a): Display images and compute the MSE of each noisy image
%

xx = (XNhi - X).^2;
MSE_Nhi = mean(xx(:));
disp(['MSE girl2Noise32Hi.bin:  ' num2str(MSE_Nhi)])
xx = (XN - X).^2;
MSE_N = mean(xx(:));
disp(['MSE girl2Noise32.bin:    ' num2str(MSE_N)])
disp(' ');

figure(1);image(X);colormap(gray(256));axis('image','off');
title('Original Tiffany Image','FontSize',18);
print -deps Mgirl2.eps;
figure(2);image(XNhi);colormap(gray(256));axis('image','off');
title('girl2Noise32Hi','FontSize',18);
print -deps Mgirl2Noise32Hi.eps;
figure(3);image(XN);colormap(gray(256));axis('image','off');
title('girl2Noise32','FontSize',18);
print -deps Mgirl2Noise32.eps;

%----------------------------------------------------------------------
%
% P2(b): Apply isotropic ideal LPF with U_cutoff = 64.
%   Use circular convolution for this.
%

U_cutoff = 64;
[U,V] = meshgrid(-128:127,-128:127);
```

```
HLtildeCenter = double(sqrt(U.^2 + V.^2) <= U_cutoff);
HLtilde = fftshift(HLtildeCenter);

% apply to original girl2 image and compute MSE
Y1 = ifft2(fft2(X) .* HLtilde);
yy = (Y1 - X).^2;
MSE_Y1 = mean(yy(:));
disp(['MSE:  ideal LPF on girl2:      ' num2str(MSE_Y1)])

% apply to image with hi pass noise; compute MSE and ISNR
Y1Nhi = ifft2(fft2(XNhi) .* HLtilde);
yy = (Y1Nhi - X).^2;
MSE_Y1Nhi = mean(yy(:));
disp(['MSE:  ideal LPF on Noise32Hi:  ' num2str(MSE_Y1Nhi)])
ISNR_Y1Nhi = 10*log10(MSE_Nhi/MSE_Y1Nhi);
disp(['ISNR: ideal LPF on Noise32Hi:  ' num2str(ISNR_Y1Nhi) ' dB'])

% apply to image with broadband noise; compute MSE and ISNR
Y1N = ifft2(fft2(XN) .* HLtilde);
yy = (Y1N - X).^2;
MSE_Y1N = mean(yy(:));
disp(['MSE:  ideal LPF on Noise32:    ' num2str(MSE_Y1N)])
ISNR_Y1N = 10*log10(MSE_N/MSE_Y1N);
disp(['ISNR: ideal LPF on Noise32:    ' num2str(ISNR_Y1N) ' dB'])
disp(' ');

figure(4);image(stretch(Y1));colormap(gray(256));axis('image','off');
title('LPF on girl2','FontSize',18);
print -deps MY1.eps;
figure(5);image(stretch(Y1Nhi));colormap(gray(256));axis('image','off');
title('LPF on Noise32Hi','FontSize',18);
print -deps MY1Nhi.eps;
figure(6);image(stretch(Y1N));colormap(gray(256));axis('image','off');
title('LPF on Noise32','FontSize',18);
print -deps MY1N.eps;

%----------------------------------------------------------------------
%
% P2(c): Use the method of Example 4 p. 5.65 to apply Gaussian
% LPF with U_cutoff = 64.
%

U_cutoff_G = 64;
SigmaG = 0.19 * 256 / U_cutoff_G;
[U,V] = meshgrid(-128:127,-128:127);
GtildeCenter = exp((-2*pi^2*SigmaG^2)/(256.^2)*(U.^2 + V.^2));
Gtilde = fftshift(GtildeCenter);
G  = ifft2(Gtilde);
G2 = fftshift(G);
```

```
ZPG2 = zeros(512,512);
ZPG2(1:256,1:256) = G2;

% apply to original girl2 image and compute MSE
ZPX = zeros(512,512);
ZPX(1:256,1:256) = X;
yy = ifft2(fft2(ZPX).*fft2(ZPG2));
Y2 = yy(129:384,129:384);
yy = (Y2 - X).^2;
MSE_Y2 = mean(yy(:));
disp(['MSE:  Gaussian LPF on girl2:     ' num2str(MSE_Y2)])

% apply to image with hi pass noise; compute MSE and ISNR
ZPX = zeros(512,512);
ZPX(1:256,1:256) = XNhi;
yy = ifft2(fft2(ZPX).*fft2(ZPG2));
Y2Nhi = yy(129:384,129:384);
yy = (Y2Nhi - X).^2;
MSE_Y2Nhi = mean(yy(:));
disp(['MSE:  Gaussian LPF on Noise32Hi: ' num2str(MSE_Y2Nhi)])
ISNR_Y2Nhi = 10*log10(MSE_Nhi/MSE_Y2Nhi);
disp(['ISNR: Gaussian LPF on Noise32Hi: ' num2str(ISNR_Y2Nhi) ' dB'])

% apply to image with broadband noise; compute MSE and ISNR
ZPX = zeros(512,512);
ZPX(1:256,1:256) = XN;
yy = ifft2(fft2(ZPX).*fft2(ZPG2));
Y2N = yy(129:384,129:384);
yy = (Y2N - X).^2;
MSE_Y2N = mean(yy(:));
disp(['MSE:  Gaussian LPF on Noise32:   ' num2str(MSE_Y2N)])
ISNR_Y2N = 10*log10(MSE_N/MSE_Y2N);
disp(['ISNR: Gaussian LPF on Noise32:   ' num2str(ISNR_Y2N) ' dB'])
disp(' ');

figure(7);image(stretch(Y2));colormap(gray(256));axis('image','off');
title('Gauss1 on girl2','FontSize',18);
print -deps MY2.eps;
figure(8);image(stretch(Y2Nhi));colormap(gray(256));axis('image','off');
title('Gauss1 on Noise32Hi','FontSize',18);
print -deps MY2Nhi.eps;
figure(9);image(stretch(Y2N));colormap(gray(256));axis('image','off');
title('Gauss1 on Noise32','FontSize',18);
print -deps MY2N.eps;

%-----------------------------------------------------------------------
%
% P2(d): Use the method of Example 4 p. 5.65 to apply Gaussian
% LPF with U_cutoff = 77.5.
```

```
%

U_cutoff_G = 77.5;
SigmaG = 0.19 * 256 / U_cutoff_G;
GtildeCenter = exp((-2*pi^2*SigmaG^2)/(256.^2)*(U.^2 + V.^2));
Gtilde = fftshift(GtildeCenter);
G  = ifft2(Gtilde);
G2 = fftshift(G);
ZPG2 = zeros(512,512);
ZPG2(1:256,1:256) = G2;

% apply to original girl2 image and compute MSE
ZPX = zeros(512,512);
ZPX(1:256,1:256) = X;
yy = ifft2(fft2(ZPX).*fft2(ZPG2));
Y3 = yy(129:384,129:384);
yy = (Y3 - X).^2;
MSE_Y3 = mean(yy(:));
disp(['MSE:  Gaussian2 LPF on girl2:     ' num2str(MSE_Y3)])

% apply to image with hi pass noise; compute MSE and ISNR
ZPX = zeros(512,512);
ZPX(1:256,1:256) = XNhi;
yy = ifft2(fft2(ZPX).*fft2(ZPG2));
Y3Nhi = yy(129:384,129:384);
yy = (Y3Nhi - X).^2;
MSE_Y3Nhi = mean(yy(:));
disp(['MSE:  Gaussian2 LPF on Noise32Hi: ' num2str(MSE_Y3Nhi)])
ISNR_Y3Nhi = 10*log10(MSE_Nhi/MSE_Y3Nhi);
disp(['ISNR: Gaussian2 LPF on Noise32Hi: ' num2str(ISNR_Y3Nhi) ' dB'])

% apply to image with broadband noise; compute MSE and ISNR
ZPX = zeros(512,512);
ZPX(1:256,1:256) = XN;
yy = ifft2(fft2(ZPX).*fft2(ZPG2));
Y3N = yy(129:384,129:384);
yy = (Y3N - X).^2;
MSE_Y3N = mean(yy(:));
disp(['MSE:  Gaussian2 LPF on Noise32:   ' num2str(MSE_Y3N)])
ISNR_Y3N = 10*log10(MSE_N/MSE_Y3N);
disp(['ISNR: Gaussian2 LPF on Noise32:   ' num2str(ISNR_Y3N) ' dB'])

figure(10);image(stretch(Y3));colormap(gray(256));axis('image','off');
title('Gauss2 on girl2','FontSize',18);
print -deps MY3.eps;
figure(11);image(stretch(Y3Nhi));colormap(gray(256));axis('image','off');
title('Gauss2 on Noise32Hi','FontSize',18);
print -deps MY3Nhi.eps;
figure(12);image(stretch(Y3N));colormap(gray(256));axis('image','off');
```

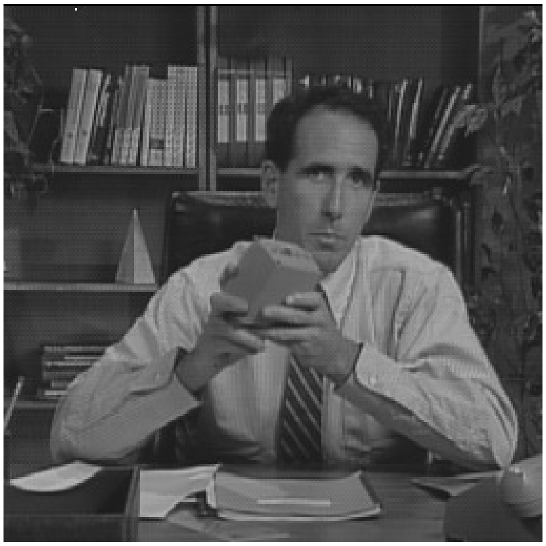
```
title('Gauss2 on Noise32','FontSize',18);
print -deps MY3N.eps;
```

C Solution:

1.

(a)

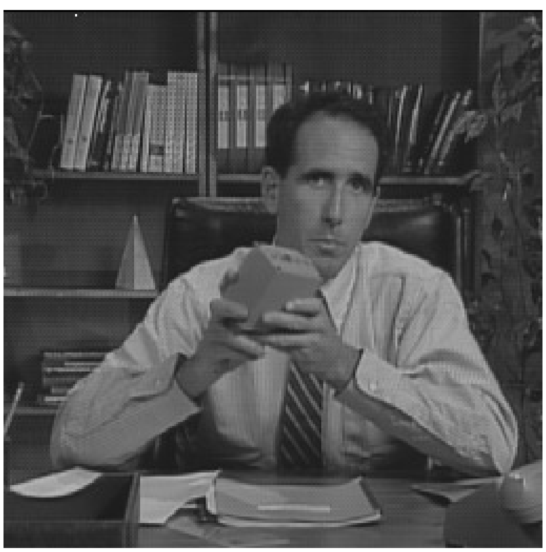
Original Image



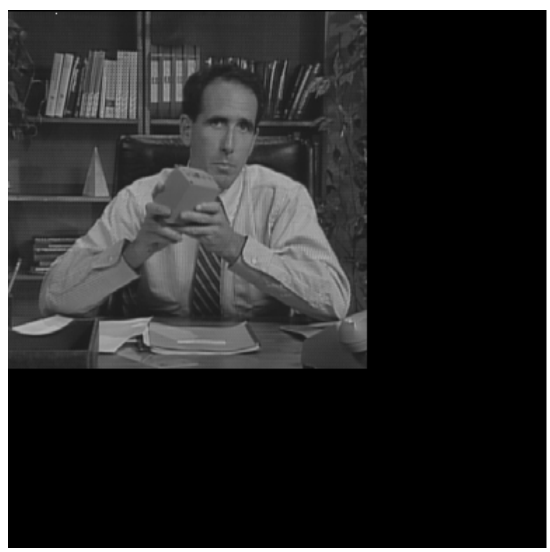
Filtered Image

(b)

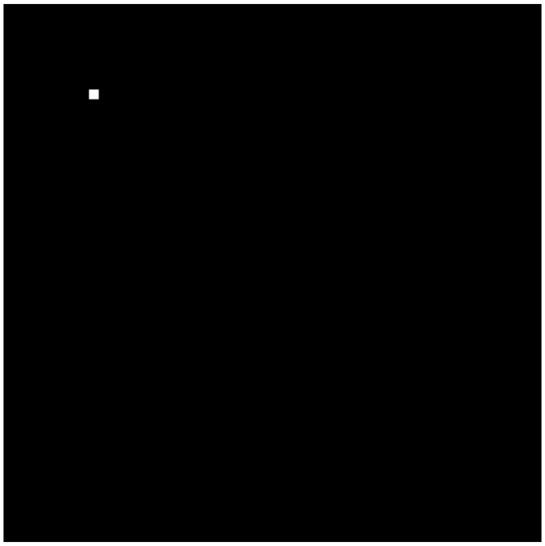
Original Image



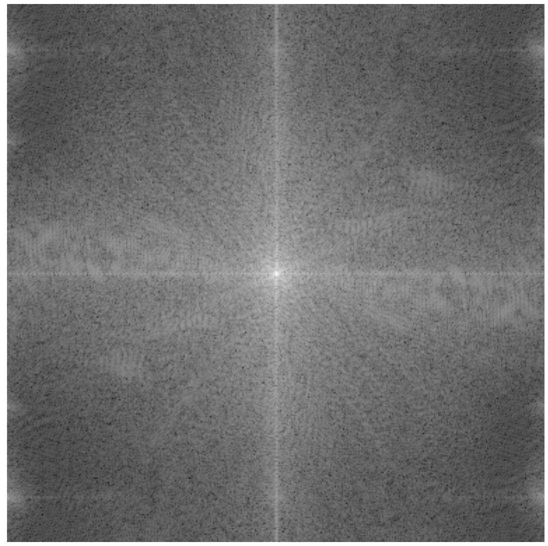
Zero Padded Image



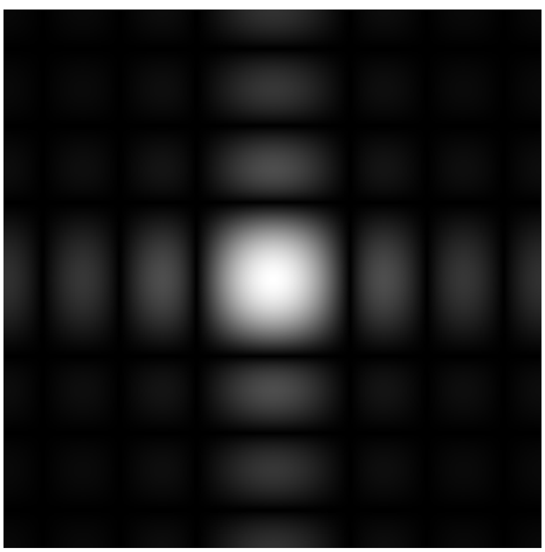
Zero Padded Impulse Response



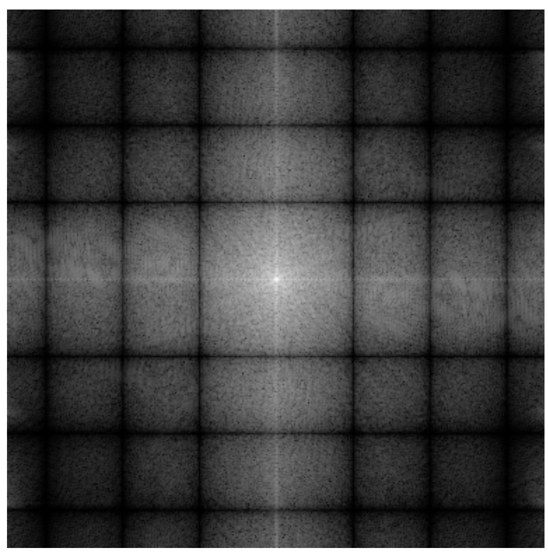
Log-Magnitude Spectrum of Zero Padded Image



Log-Magnitude Spectrum of Zero Padded H Image



Log-Magnitude Spectrum of Zero Padded Result



Zero Padded Result

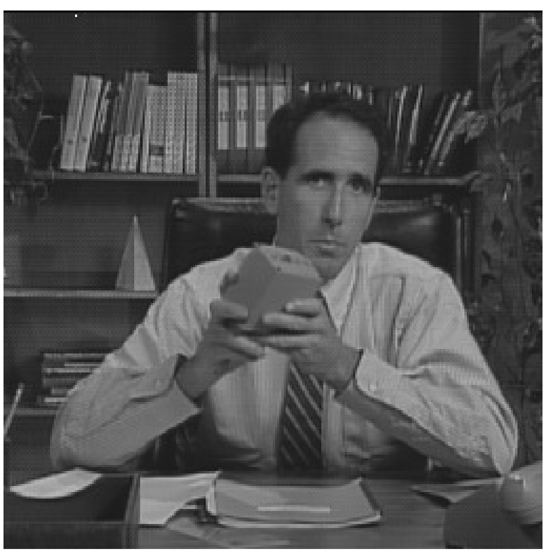
Final Filtered Image

Console output:

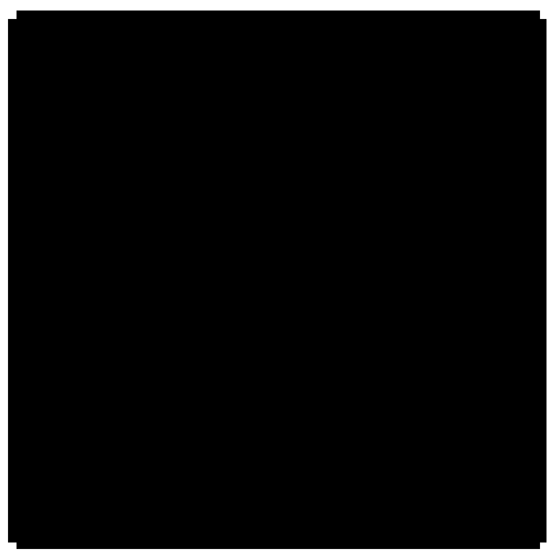
```
(b): max difference from part (a): 0.00
```

(c)

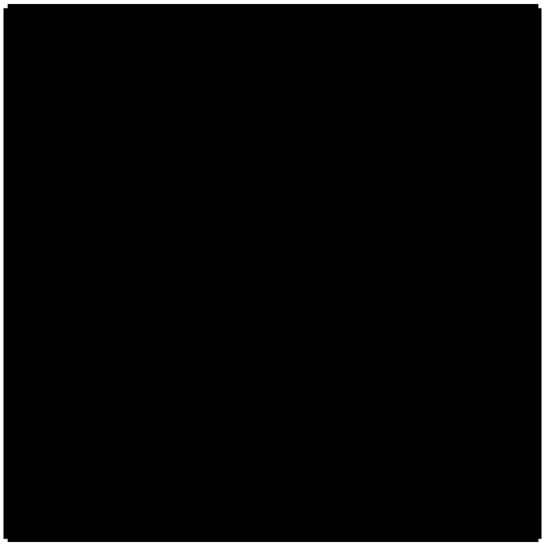
Original Image



Zero Phase Impulse Response



Zero Padded Zero-Phase H Image



Final Filtered Image

Console output:

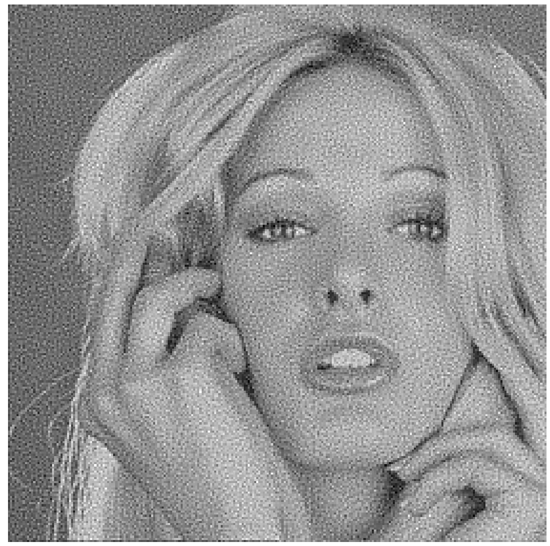
```
(c): max difference from part (a): 0.00
```

2.

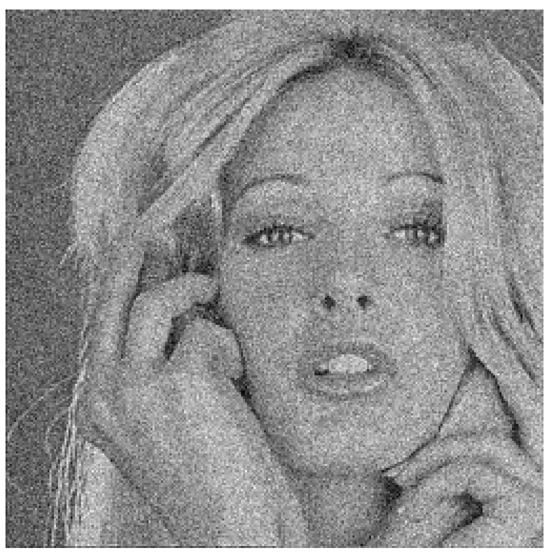
(a)

Original Tiffany Image

girl2Noise32Hi



girl2Noise32



Console output:

```
MSE girl2Noise32Hi.bin:  692.5050
MSE girl2Noise32.bin:    744.4679
```

(b)

LPF on girl2

LPF on Noise32Hi

LPF on Noise32

Console output:

```
MSE:  ideal LPF on girl2:      127.7481
MSE:  ideal LPF on Noise32Hi:  398.9978
ISNR: ideal LPF on Noise32Hi:  2.3945 dB
MSE:  ideal LPF on Noise32:    550.8787
ISNR: ideal LPF on Noise32:    1.3079 dB
```

(c)

Gauss1 on girl2

Gauss1 on Noise32Hi

Gauss1 on Noise32

Console output:

```
MSE:  Gaussian LPF on girl2:     91.2585
MSE:  Gaussian LPF on Noise32Hi: 415.8218
ISNR: Gaussian LPF on Noise32Hi: 2.2152 dB
MSE:  Gaussian LPF on Noise32:   534.7740
ISNR: Gaussian LPF on Noise32:   1.4368 dB
```

(d)

Gauss2 on girl2

Gauss2 on Noise32Hi

Gauss2 on Noise32

Matlab command window output:

```
MSE:  Gaussian2 LPF on girl2:     60.6184
MSE:  Gaussian2 LPF on Noise32Hi: 406.7896
ISNR: Gaussian2 LPF on Noise32Hi: 2.3105 dB
MSE:  Gaussian2 LPF on Noise32:   527.7709
ISNR: Gaussian2 LPF on Noise32:   1.4940 dB
```

C program listing:

```
//
// hw05.c
//
// This program requires an fftw3 installation.  See the course web site for
// details of how to install.
//
// To compile:
// gcc hw05.c -o hw05 -lfftw3 -lm
//
// 3/22/2017 jph
//

#include <math.h>
#include <stdio.h>
#include <stdlib.h>
#include <fcntl.h>
#include <string.h>

#include "fftw3.h"

#define BYTE unsigned char

//
// Function prototypes
//
void   disk2byte();
void   byte2disk();
void   fft2d();
BYTE  *f2b_FullScale();
float  L2Norm();
void   fCMult();
float  fMSE();
float  fISNR();
void   PrintMaxDiffB();
BYTE  *Problem1a();
BYTE  *Problem1b();
BYTE  *Problem1c();
void   Problem2a();
void   Problem2b();
void   Problem2c();
void   Problem2d();



/*----------------------------------------------------------------------*/
/*   MAIN                                                               */
/*----------------------------------------------------------------------*/
```

```
main(argc,argv)

  int     argc;
  char   *argv[];
{

  BYTE   *y1a;                    // BYTE result from 1(a)
  BYTE   *y1b;                    // BYTE result from 1(b)
  BYTE   *y1c;                    // BYTE result from 1(c)

  //
  // Problem 1
  //
  y1a = Problem1a(argv[0]);
  y1b = Problem1b(argv[0]);
  PrintMaxDiffB(y1a,y1b,256,'b','a');
  y1c = Problem1c(argv[0]);
  PrintMaxDiffB(y1a,y1c,256,'c','a');

  //
  // Problem 2
  //
  Problem2a(argv[0]);
  Problem2b(argv[0]);
  Problem2c(argv[0]);
  Problem2d(argv[0]);

  //
  // Collect the garbage
  //
  free(y1a);
  free(y1b);
  free(y1c);

  return;
} /*---------------   MAIN   -------------------------------------------*/

/*----------------------------------------------------------------------
 * Problem1a
 *
 *   HW 5, Problem 1(a).
 *
 *   - read in salesman.bin as a BYTE image
 *   - apply a 7x7 average filter in the image domain
 *       - handle edge effects by zero padding
 *   - write output image as BYTE with full-scale contrast
 *
 *  jph 23 March 2017
```

```
 *
 ----------------------------------------------------------------------*/

BYTE *Problem1a(cmd)

  char    *cmd;                   // command used to invoke this program
{

  int      i;                     // loop counter
  int      size;                  // num rows/cols in image
  int      size2;                 // size + 6
  int      N;                     // size * size
  int      N2;                    // size2 * size2
  int      row;                   // row counter
  int      row2;                  // row counter in padded image
  int      col;                   // col counter
  int      col2;                  // col counter in padded image
  int      Wrow;                  // row in window
  int      Wcol;                  // col in window
  float    one_on_49;             // 1/49
  BYTE    *xb;                    // BYTE input image
  float   *xf2;                   // zero padded float input image
  BYTE    *yb;                    // BYTE ouptput image
  float   *yf;                    // float output image; 256 x 256

  printf("\nDoing Problem 1(a)...\n");
  size = 256;
  size2 = size + 6;
  N = size * size;
  N2 = size2 * size2;

  //
  // Allocate image arrays
  //
  if ((xb = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
    printf("\n%s: free store exhausted in Problem 1(a).\n",cmd);
    exit(-1);
  }
  if ((xf2 = (float*)malloc(size2*size2*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 1(a).\n",cmd);
    exit(-1);
  }
  if ((yb = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
    printf("\n%s: free store exhausted in Problem 1(a).\n",cmd);
    exit(-1);
  }
  if ((yf = (float*)malloc(size*size*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 1(a).\n",cmd);
    exit(-1);
```

```
}

//
// Read the input image
//
disk2byte(xb,size,size,"salesman.bin");

//
// Cast to float and zero pad to 262 x 262
//
for (i=0; i < N2; i++) {
  xf2[i] = (float)0.0;
}
for (i=0,row=3; row < size2-3; row++) {
  for (col=3; col < size2-3; col++,i++) {
    xf2[row*size2 + col] = (float)xb[i];
  }    // for row
}      // for col

//
// Initialize output float image
//
for (i=0; i < N; i++) {
  yf[i] = (float)0.0;
}

//
// Apply the 7x7 average filter
//
one_on_49 = (float)1.0 / (float)49.0;
for (row=0,row2=3; row < size; row++,row2++) {
  for (col=0,col2=3; col < size; col++,col2++) {
    for (Wrow=row2-3; Wrow <= row2+3; Wrow++) {
      for (Wcol=col2-3; Wcol <= col2+3; Wcol++) {
        yf[row*size + col] += xf2[Wrow*size2 + Wcol];
      }  // for Wcol
    }    // for Wrow
    yf[row*size + col] = one_on_49 * yf[row*size + col];
  }      // for col
}        // for row

//
// Apply full-scale stretch to output image and cast to BYTE
//
yb = f2b_FullScale(yf,size,cmd);

//
// Write the output image to disk
//
```

```
  byte2disk(yb,size,size,"CY1a.bin");

  //
  // Collect the garbage
  //
  free(xb);
  free(xf2);
  free(yf);

  //
  // Return the BYTE result
  //
  return(yb);
} /*---------------------  Problem1a  --------------------------------*/

/*----------------------------------------------------------------------
 * Problem1b
 *
 *   HW 5, Problem 1(b).
 *
 *   Use the method of Example 3 on page 5.61 of the Notes to do the
 *   same linear convolution as in Problem 1(a) (7x7 average filter)
 *   by pointwise multiplication of DFT's.
 *
 *   The impulse response image H will be 128x128.
 *
 *  jph 23 March 2017
 *
 ----------------------------------------------------------------------*/

BYTE *Problem1b(cmd)

  char    *cmd;                   // command used to invoke this program
{

  int      i;                     // loop counter
  int      size;                  // num rows/cols in input image
  int      Hsize;                 // num rows/cols in H image
  int      Padsize;               // size for zero padded images
  int      p0,q0;                 // horiz & vert offsets for H image
  int      row;                   // row counter
  int      col;                   // col counter
  int      row2;                  // row counter
  int      col2;                  // col counter
  BYTE    *xb;                    // BYTE input image
  float   *xf;                    // float input image; 256 x 256
  float   *ZPxR;                  // zero-padded input image, real part
  float   *ZPxI;                  // zero-padded input image, imag part
  BYTE    *BZPxR;                 // zero-padded input image; real; BYTE
```

```
float   *XtildeR;               // Real part of FFT of zero-padded image
float   *XtildeI;               // Imag part of FFT of zero-padded image
float   *XtildeMag;             // float log-magnitude spectrum of image
BYTE    *BXtildeMag;            // BYTE  log-magnitude spectrum of image
float   *H;                     // float impulse response image
float   *ZPHR;                  // zero-padded H image, real part
float   *ZPHI;                  // zero-padded H image, imag part
BYTE    *BZPHR;                 // zero-padded H image; real; BYTE
float   *HtildeR;               // Real part of FFT of zero-padded H image
float   *HtildeI;               // Imag part of FFT of zero-padded H image
float   *HtildeMag;             // float log-magnitude spectrum of H image
BYTE    *BHtildeMag;            // BYTE  log-magnitude spectrum of H image
float   *YtildeR;               // Real part of FFT of zero-padded output
float   *YtildeI;               // Imag part of FFT of zero-padded output
float   *YtildeMag;             // float log-magnitude spectrum of Y image
BYTE    *BYtildeMag;            // BYTE  log-magnitude spectrum of Y image
float   *ZPyR;                  // zero-padded output image, real part
float   *ZPyI;                  // zero-padded output image, imag part
BYTE    *BZPyR;                 // zero-padded output image; real; BYTE
float   *yf;                    // float output image; 256 x 256
BYTE    *Byf;                   // BYTE  output image; 256 x 256

printf("\nDoing Problem 1(b)...\n");
size = 256;
Hsize = 128;
p0 = q0 = 64;

//
// Use a zero-padded size one larger than the minimum... see the
//   note for problem 1(b) in the assignment for an explanation
//
Padsize = size + Hsize;

//
// Allocate image arrays
//
if ((xb = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((xf = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((ZPxR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((ZPxI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
```

```
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((XtildeR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((XtildeI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((XtildeMag = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((ZPHR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((ZPHI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((H = (float*)malloc(Hsize*Hsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((HtildeR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((HtildeI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((HtildeMag = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((YtildeR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((YtildeI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((YtildeMag = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
```

```
  exit(-1);
}
if ((ZPyR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((ZPyI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}
if ((yf = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(b).\n",cmd);
  exit(-1);
}

//
// Read the input image
//
disk2byte(xb,size,size,"salesman.bin");

//
// Cast to float
//
for (i=0; i < size*size; i++) {
  xf[i] = (float)xb[i];
}

//
// Make the 128x128 impulse response image H
//
for (i=0; i < Hsize*Hsize; i++) {
  H[i] = (float)0.0;
}
for (row=q0-3; row <= q0+3; row++) {
  for (col=p0-3; col <= p0+3; col++) {
    H[row*Hsize + col] = (float)1.0/(float)49.0;
  }
}

//
// Zero pad both images
//
for (i=0; i < Padsize*Padsize; i++) {
  ZPxR[i] = (float)0.0;
  ZPxI[i] = (float)0.0;
  ZPHR[i] = (float)0.0;
  ZPHI[i] = (float)0.0;
}
for (row=0; row < size; row++) {
```

```
  for (col=0; col < size; col++) {
    ZPxR[row*Padsize + col] = xf[row*size + col];
  }
}
for (row=0; row < Hsize; row++) {
  for (col=0; col < Hsize; col++) {
    ZPHR[row*Padsize + col] = H[row*Hsize + col];
  }
}

//
// Write zero-padded images to disk as BYTE w/ full-scale contrast
//
BZPxR = f2b_FullScale(ZPxR,Padsize,cmd);
BZPHR = f2b_FullScale(ZPHR,Padsize,cmd);
byte2disk(BZPxR,Padsize,Padsize,"CZPX1b.bin");
byte2disk(BZPHR,Padsize,Padsize,"CZPH1b.bin");

//
// Compute DFT's of zero-padded images
//
fft2d(ZPxR,ZPxI,XtildeR,XtildeI,Padsize,1);
fft2d(ZPHR,ZPHI,HtildeR,HtildeI,Padsize,1);

//
// Write log-magnitude spectra of zero-padded input and H images
//
for (i=0; i < Padsize*Padsize; i++) {
  XtildeMag[i] = (float)log((double)1.0 + L2Norm(XtildeR[i],XtildeI[i]));
  HtildeMag[i] = (float)log((double)1.0 + L2Norm(HtildeR[i],HtildeI[i]));
}
BXtildeMag = f2b_FullScale(XtildeMag,Padsize,cmd);
BHtildeMag = f2b_FullScale(HtildeMag,Padsize,cmd);
byte2disk(BXtildeMag,Padsize,Padsize,"CZPXtilde1b.bin");
byte2disk(BHtildeMag,Padsize,Padsize,"CZPHtilde1b.bin");

//
// Compute convolution by pointwise multiplication of DFT's
//
for (i=0; i < Padsize*Padsize; i++) {
  fCMult(&YtildeR[i],&YtildeI[i],XtildeR[i],XtildeI[i],
                                HtildeR[i],HtildeI[i]);
}

//
// Write log-magnitude spectrum of zero-padded output image
//
for (i=0; i < Padsize*Padsize; i++) {
  YtildeMag[i] = (float)log((double)1.0 + L2Norm(YtildeR[i],YtildeI[i]));
```

```
}
BYtildeMag = f2b_FullScale(YtildeMag,Padsize,cmd);
byte2disk(BYtildeMag,Padsize,Padsize,"CZPYtilde1b.bin");

//
// Compute zero-padded output image by inverse DFT and write to disk
//
fft2d(ZPyR,ZPyI,YtildeR,YtildeI,Padsize,-1);
BZPyR = f2b_FullScale(ZPyR,Padsize,cmd);
byte2disk(BZPyR,Padsize,Padsize,"CZPY1b.bin");

//
// Crop to get the final 256x256 output image and write to disk
//
for (row=0,row2=q0; row < size; row++,row2++) {
  for (col=0,col2=p0; col < size; col++,col2++) {
    yf[row*size + col] = ZPyR[row2*Padsize + col2];
  }
}
Byf = f2b_FullScale(yf,size,cmd);
byte2disk(Byf,size,size,"CY1b.bin");

//
// Collect the garbage
//
free(H);
free(xb);
free(xf);
free(yf);
free(ZPxR);
free(ZPxI);
free(ZPHR);
free(ZPHI);
free(ZPyR);
free(ZPyI);
free(BZPxR);
free(BZPHR);
free(BZPyR);
free(XtildeR);
free(XtildeI);
free(HtildeR);
free(HtildeI);
free(YtildeR);
free(YtildeI);
free(XtildeMag);
free(HtildeMag);
free(YtildeMag);
free(BXtildeMag);
free(BHtildeMag);
```

```
  free(BYtildeMag);

  //
  // Return the BYTE result
  //
  return(Byf);
} /*--------------------  Problem1b  -------------------------------*/

/*----------------------------------------------------------------------
 * Problem1c
 *
 *   HW 5, Problem 1(c).
 *
 *   Use the method of Example 5 on page 5.76 of the Notes to do the
 *   same linear convolution as in Problems 1(a) and (b) (7x7 average
 *   filter) by pointwise multiplication of the DFT of the zero-padded image
 *   with the DFT of the correctly zero-padded zero-phase impulse response.
 *
 *   The zero-phase impulse response image H will be 256x256.
 *
 *  jph 25 March 2017
 *
 ----------------------------------------------------------------------*/

BYTE *Problem1c(cmd)

  char    *cmd;                   // command used to invoke this program
{

  int      i;                     // loop counter
  int      size;                  // num rows/cols in input image
  int      so2;                   // size / 2
  int      Padsize;               // size for zero padded images
  int      p0,q0;                 // horiz & vert offsets for H image
  int      row;                   // row counter
  int      col;                   // col counter
  BYTE    *xb;                    // BYTE  input  image; 256 x 256
  float   *xf;                    // float input  image; 256 x 256
  float   *ZPxR;                  // zero-padded input image, real part
  float   *ZPxI;                  // zero-padded input image, imag part
  float   *XtildeR;               // Real part of FFT of zero-padded image
  float   *XtildeI;               // Imag part of FFT of zero-padded image
  float   *H;                     // float impulse response image
  float   *H2;                    // float zero-phase impulse response image
  float   *ZPH2R;                 // zero-padded H2 image, real part
  float   *ZPH2I;                 // zero-padded H2 image, imag part
  BYTE    *H2b;                   // BYTE  zero-phase impulse response image
  BYTE    *ZPH2b;                 // BYTE  zero-padded H2 image
  float   *H2tildeR;              // Real part of FFT of zero-padded H2 image
```

```
float   *H2tildeI;              // Imag part of FFT of zero-padded H2 image
float   *YtildeR;               // Real part of FFT of zero-padded output
float   *YtildeI;               // Imag part of FFT of zero-padded output
float   *ZPyR;                  // zero-padded output image, real part
float   *ZPyI;                  // zero-padded output image, imag part
float   *yf;                    // float output image; 256 x 256
BYTE    *yb;                    // BYTE  output image; 256 x 256


printf("\nDoing Problem 1(c)...\n");
size = 256;
so2 = size/2;
Padsize = size*2;
p0 = q0 = 128;

//
// Allocate image arrays
//
if ((xb = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((xf = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((ZPxR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((ZPxI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((XtildeR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((XtildeI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((H = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((H2 = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
```

```
}
if ((ZPH2R = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((ZPH2I = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((H2tildeR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((H2tildeI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((YtildeR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((YtildeI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((ZPyR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((ZPyI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}
if ((yf = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 1(c).\n",cmd);
  exit(-1);
}

//
// Read the input image
//
disk2byte(xb,size,size,"salesman.bin");

//
// Cast to float
//
for (i=0; i < size*size; i++) {
  xf[i] = (float)xb[i];
}
```

```
//
// Make the 256x256 impulse response image H w/ the square in the center
//
for (i=0; i < size*size; i++) {
  H[i] = (float)0.0;
}
for (row=q0-3; row <= q0+3; row++) {
  for (col=p0-3; col <= p0+3; col++) {
    H[row*size + col] = (float)1.0/(float)49.0;
  }
}

//
// Permute the quadrants of the H image to get the true zero-phase
//   impulse response image H2 as explained on pp. 5.68-5.71 of course Notes.
//   This is equivalent to the Matlab fftshift routine.
//
for (row=0; row < so2; row++) {
  for (col=0; col < so2; col++) {

    // Quadrant I
    H2[row*size + col] = H[(row+so2)*size + (col+so2)];

    // Quadrant II
    H2[row*size + (col+so2)] = H[(row+so2)*size + col];

    // Quadrant III
    H2[(row+so2)*size + (col+so2)] = H[row*size + col];

    // Quadrant IV
    H2[(row+so2)*size + col] = H[row*size + (col+so2)];

  }    // for col
}      // for row

//
// Write H2 to disk as BYTE w/ full-scale contrast
//
H2b = f2b_FullScale(H2,size,cmd);
byte2disk(H2b,size,size,"CH1c.bin");

//
// Zero pad the input image
//
for (i=0; i < Padsize*Padsize; i++) {
  ZPxR[i] = (float)0.0;
  ZPxI[i] = (float)0.0;
}
```

```
for (row=0; row < size; row++) {
  for (col=0; col < size; col++) {
    ZPxR[row*Padsize + col] = xf[row*size + col];
  }
}

//
// Make the zero-padded impulse response image as in Example 5
//   on page 5.76 of the notes.
//
for (i=0; i < Padsize*Padsize; i++) {
  ZPH2R[i] = ZPH2I[i] = (float)0.0;
}
for (row=0; row < so2; row++) {
  for (col=0; col < so2; col++) {
    ZPH2R[row*Padsize + col] = H2[row*size + col];
    ZPH2R[row*Padsize + (Padsize-so2+col)] = H2[row*size + (col+so2)];
    ZPH2R[(Padsize-so2+row)*Padsize + col] = H2[(row+so2)*size + col];
    ZPH2R[(Padsize-so2+row)*Padsize + (Padsize-so2+col)]
                                      = H2[(row+so2)*size + (col+so2)];
  }  // for col
}    // for row

//
// Write zero-padded H2 image to disk w/ full-scale contrast
//
ZPH2b = f2b_FullScale(ZPH2R,Padsize,cmd);
byte2disk(ZPH2b,Padsize,Padsize,"CZPH1c.bin");

//
// Compute the filtered image by pointwise multiplication of DFT's
//
fft2d(ZPxR,ZPxI,XtildeR,XtildeI,Padsize,1);
fft2d(ZPH2R,ZPH2I,H2tildeR,H2tildeI,Padsize,1);
for (i=0; i < Padsize*Padsize; i++) {
  fCMult(&YtildeR[i],&YtildeI[i],XtildeR[i],XtildeI[i],
                                 H2tildeR[i],H2tildeI[i]);
}
fft2d(ZPyR,ZPyI,YtildeR,YtildeI,Padsize,-1);

//
// Crop to get the final 256x256 output image and write to disk
//
for (row=0; row < size; row++) {
  for (col=0; col < size; col++) {
    yf[row*size + col] = ZPyR[row*Padsize + col];
  }
}
yb = f2b_FullScale(yf,size,cmd);
```

```
  byte2disk(yb,size,size,"CY1c.bin");

  //
  // Collect the garbage
  //
  free(H);
  free(H2);
  free(xb);
  free(xf);
  free(yf);
  free(H2b);
  free(ZPxR);
  free(ZPxI);
  free(ZPyR);
  free(ZPyI);
  free(ZPH2R);
  free(ZPH2I);
  free(ZPH2b);
  free(XtildeR);
  free(XtildeI);
  free(YtildeR);
  free(YtildeI);
  free(H2tildeR);
  free(H2tildeI);

  //
  // Return the BYTE result
  //
  return(yb);
} /*---------------------  Problem1c  ---------------------------------*/

/*----------------------------------------------------------------------
 * Problem2a
 *
 *   HW 5, Problem 2(a)
 *
 *   Read images:
 *     - girl2.bin
 *     - girl2Noise32Hi.bin
 *     - girl2Noise32.bin
 *
 *  Compute MSE of girl2Noise32Hi.bin and girl2Noise32.bin
 *
 *  jph 25 March 2017
 *
 -----------------------------------------------------------------------*/

void Problem2a(cmd)
```

```
  char    *cmd;                  // command used to invoke this program
{

  int      i;                    // loop counter
  int      size;                 // num rows/cols in input image
  int      so2;                  // size / 2
  BYTE    *xb;                   // BYTE  image: girl2.bin
  float   *xf;                   // float image: girl2.bin
  BYTE    *xNb;                  // BYTE  image: girl2Noise32.bin
  float   *xNf;                  // float image: girl2Noise32.bin
  BYTE    *xNhib;                // BYTE  image: girl2Noise32Hi.bin
  float   *xNhif;                // float image: girl2Noise32Hi.bin
  float    MSE_N;                // MSE of girl2Noise32.bin
  float    MSE_Nhi;              // MSE of girl2Noise32Hi.bin

  printf("\nDoing Problem 2(a)...\n");
  size = 256;
  so2 = size/2;

  //
  // Allocate image arrays
  //
  if ((xb = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(a).\n",cmd);
    exit(-1);
  }
  if ((xf = (float*)malloc(size*size*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(a).\n",cmd);
    exit(-1);
  }
  if ((xNb = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(a).\n",cmd);
    exit(-1);
  }
  if ((xNf = (float*)malloc(size*size*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(a).\n",cmd);
    exit(-1);
  }
  if ((xNhib = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(a).\n",cmd);
    exit(-1);
  }
  if ((xNhif = (float*)malloc(size*size*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(a).\n",cmd);
    exit(-1);
  }

  //
  // Read images
```

```
  //
  disk2byte(xb,size,size,"girl2.bin");
  disk2byte(xNb,size,size,"girl2Noise32.bin");
  disk2byte(xNhib,size,size,"girl2Noise32Hi.bin");

  //
  // Cast to float
  //
  for (i=0; i < size*size; i++) {
    xf[i] = (float)xb[i];
    xNf[i] = (float)xNb[i];
    xNhif[i] = (float)xNhib[i];
  }

  //
  // Compute MSE and print to console
  //
  MSE_Nhi = fMSE(xf,xNhif,size);
  MSE_N = fMSE(xf,xNf,size);
  printf("\nMSE girl2Noise32Hi.bin:  %.4f",MSE_Nhi);
  printf("\nMSE girl2Noise32.bin:    %.4f\n",MSE_N);

  //
  // Collect the garbage
  //
  free(xb);
  free(xf);
  free(xNb);
  free(xNf);
  free(xNhib);
  free(xNhif);

  return;
} /*--------------------  Problem2a  --------------------------------*/

/*-------------------------------------------------------------------
 * Problem2b
 *
 *   HW 5, Problem 2(b)
 *
 *   Read images:
 *     - girl2.bin
 *     - girl2Noise32Hi.bin
 *     - girl2Noise32.bin
 *
 *  Use circular convolution to apply an ideal isotropic LPF with
 *  U_cutoff = 64 cpi.
 *
 *  jph 25 March 2017
```

```
 *
 -----------------------------------------------------------------------*/

void Problem2b(cmd)

  char    *cmd;                   // command used to invoke this program
{

  int      i;                     // loop counter
  int      size;                  // num rows/cols in input image
  int      so2;                   // size/2
  int      row;                   // row counter
  int      col;                   // col counter
  float    MSE;                   // mean squared error
  float    ISNR;                  // improvement in SNR
  float    U_cutoff;              // LPF cutoff frequency in cpi
  float    U;                     // horiz freq in cpi
  float    V;                     // vert  freq in cpi
  BYTE    *xb;                    // BYTE  image: girl2.bin
  float   *xf;                    // float image: girl2.bin
  BYTE    *xNb;                   // BYTE  image: girl2Noise32.bin
  float   *xNf;                   // float image: girl2Noise32.bin
  BYTE    *xNhib;                 // BYTE  image: girl2Noise32Hi.bin
  float   *xNhif;                 // float image: girl2Noise32Hi.bin
  float   *HtildeCenter;          // centered frequency response image
  float   *fzero;                 // floating point zero image
  float   *fzero2;                // floating point zero image
  float   *XtildeR;               // Real part of DFT of input image
  float   *XtildeI;               // Imag part of DFT of input image
  float   *YtildeR;               // Real part of DFT of output image
  float   *YtildeI;               // Imag part of DFT of output image
  float   *yf;                    // float output image
  BYTE    *yb;                    // BYTE  output image

  printf("\nDoing Problem 2(b)...\n");
  size = 256;
  so2 = size/2;

  //
  // Allocate image arrays
  //
  if ((xb = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(b).\n",cmd);
    exit(-1);
  }
  if ((xf = (float*)malloc(size*size*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(b).\n",cmd);
    exit(-1);
  }
```

```
if ((xNb = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(b).\n",cmd);
  exit(-1);
}
if ((xNf = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(b).\n",cmd);
  exit(-1);
}
if ((xNhib = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(b).\n",cmd);
  exit(-1);
}
if ((xNhif = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(b).\n",cmd);
  exit(-1);
}
if ((HtildeCenter = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(b).\n",cmd);
  exit(-1);
}
if ((fzero = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(b).\n",cmd);
  exit(-1);
}
if ((fzero2 = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(b).\n",cmd);
  exit(-1);
}
if ((XtildeR = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(b).\n",cmd);
  exit(-1);
}
if ((XtildeI = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(b).\n",cmd);
  exit(-1);
}
if ((YtildeR = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(b).\n",cmd);
  exit(-1);
}
if ((YtildeI = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(b).\n",cmd);
  exit(-1);
}
if ((yf = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(b).\n",cmd);
  exit(-1);
}
```

```
//
// Read images
//
disk2byte(xb,size,size,"girl2.bin");
disk2byte(xNb,size,size,"girl2Noise32.bin");
disk2byte(xNhib,size,size,"girl2Noise32Hi.bin");

//
// Cast to float
//
for (i=0; i < size*size; i++) {
  xf[i] = (float)xb[i];
  xNf[i] = (float)xNb[i];
  xNhif[i] = (float)xNhib[i];
}
//
// Read images
//
disk2byte(xb,size,size,"girl2.bin");
disk2byte(xNb,size,size,"girl2Noise32.bin");
disk2byte(xNhib,size,size,"girl2Noise32Hi.bin");

//
// Cast to float
//
for (i=0; i < size*size; i++) {
  xf[i] = (float)xb[i];
  xNf[i] = (float)xNb[i];
  xNhif[i] = (float)xNhib[i];
}

//
// Design the centered frequency response image
//
U_cutoff = 64.0;
for (row=0; row < size; row++) {
  for (col=0; col < size; col++) {
    U = (float)(col - so2);
    V = (float)(row - so2);
    if (L2Norm(U,V) <= U_cutoff) {
      HtildeCenter[row*size + col] = (float)1.0;
    } else {
      HtildeCenter[row*size + col] = (float)0.0;
    }    // else
  }      // for col
}        // for row

//
// Make floating point zero images
```

```
//
for (i=0; i < size*size; i++) {
  fzero[i] = fzero2[i] = (float)0.0;
}

//
// Use DFT to apply the filter to girl2
//
fft2d(xf,fzero,XtildeR,XtildeI,size,1);
for (i=0; i < size*size; i++) {
  fCMult(&YtildeR[i],&YtildeI[i],XtildeR[i],XtildeI[i],
                                HtildeCenter[i],fzero[i]);
}
fft2d(yf,fzero2,YtildeR,YtildeI,size,-1);

//
// Compute MSE and write the output image to disk as BYTE
//
MSE = fMSE(xf,yf,size);
printf("\nMSE:  ideal LPF on girl2:      %.4f",MSE);
yb = f2b_FullScale(yf,size,cmd);
byte2disk(yb,size,size,"CY1.bin");
free(yb);

//
// Use DFT to apply the filter to girl2Noise32Hi
//
fft2d(xNhif,fzero,XtildeR,XtildeI,size,1);
for (i=0; i < size*size; i++) {
  fCMult(&YtildeR[i],&YtildeI[i],XtildeR[i],XtildeI[i],
                                HtildeCenter[i],fzero[i]);
}
fft2d(yf,fzero2,YtildeR,YtildeI,size,-1);

//
// Compute MSE and ISNR; write output image as BYTE
//
MSE = fMSE(xf,yf,size);
printf("\nMSE:  ideal LPF on Noise32Hi:  %.4f",MSE);
ISNR = fISNR(xf,xNhif,yf,size);
printf("\nISNR: ideal LPF on Noise32Hi:  %.4f dB",ISNR);
yb = f2b_FullScale(yf,size,cmd);
byte2disk(yb,size,size,"CY1Nhi.bin");
free(yb);

//
// Use DFT to apply the filter to girl2Noise32
//
fft2d(xNf,fzero,XtildeR,XtildeI,size,1);
```

```
  for (i=0; i < size*size; i++) {
    fCMult(&YtildeR[i],&YtildeI[i],XtildeR[i],XtildeI[i],
                                  HtildeCenter[i],fzero[i]);
  }
  fft2d(yf,fzero2,YtildeR,YtildeI,size,-1);

  //
  // Compute MSE and ISNR; write output image as BYTE
  //
  MSE = fMSE(xf,yf,size);
  printf("\nMSE:  ideal LPF on Noise32:    %.4f",MSE);
  ISNR = fISNR(xf,xNf,yf,size);
  printf("\nISNR: ideal LPF on Noise32:    %.4f dB\n",ISNR);
  yb = f2b_FullScale(yf,size,cmd);
  byte2disk(yb,size,size,"CY1N.bin");
  free(yb);

  //
  // Collect the garbage
  //
  free(xb);
  free(xf);
  free(xNb);
  free(xNf);
  free(xNhib);
  free(xNhif);
  free(fzero);
  free(fzero2);
  free(XtildeR);
  free(XtildeI);
  free(YtildeR);
  free(YtildeI);
  free(HtildeCenter);

  return;
} /*---------------------  Problem2b  --------------------------------*/

/*--------------------------------------------------------------------
 * Problem2c
 *
 *   HW 5, Problem 2(c)
 *
 *   Read images:
 *     - girl2.bin
 *     - girl2Noise32Hi.bin
 *     - girl2Noise32.bin
 *
 *  Use the method of Example 4 on page 5.65 of the course notes
 *  to apply a Gaussian LPF with U_cutoff = 64 cpi.
```

```
 *
 *  jph 25 March 2017
 *
 -------------------------------------------------------------------------*/

void Problem2c(cmd)

  char    *cmd;                   // command used to invoke this program
{

  int      i;                     // loop counter
  int      size;                  // num rows/cols in input image
  int      so2;                   // size/2
  int      Padsize;               // size for zero padded images
  int      row;                   // row counter
  int      col;                   // col counter
  int      row2;                  // row counter
  int      col2;                  // col counter
  float    MSE;                   // mean squared error
  float    ISNR;                  // improvement in SNR
  float    U_cutoff_G;            // LPF cutoff frequency in cpi
  float    SigmaG;                // Gaussian filter space constant
  float    U;                     // horiz freq in cpi
  float    V;                     // vert  freq in cpi
  BYTE    *xb;                    // BYTE  image: girl2.bin
  float   *xf;                    // float image: girl2.bin
  BYTE    *xNb;                   // BYTE  image: girl2Noise32.bin
  float   *xNf;                   // float image: girl2Noise32.bin
  BYTE    *xNhib;                 // BYTE  image: girl2Noise32Hi.bin
  float   *xNhif;                 // float image: girl2Noise32Hi.bin
  float   *GtildeCenter;          // centered frequency response image
  float   *Gf;                    // zero-phase impulse response image
  float   *G2f;                   // centered impulse response image
  float   *ZPG2R;                 // zero-padded G2 image, real part
  float   *ZPG2I;                 // zero-padded G2 image, imag part
  float   *GtildeR;               // FFT of ZPG2, real part
  float   *GtildeI;               // FFT of ZPG2, imag part
  float   *ZPxR;                  // zero padded input image, real part
  float   *ZPxI;                  // zero padded input image, imag part
  float   *XtildeR;               // FFT of ZPx, imag part
  float   *XtildeI;               // FFT of ZPx, imag part
  float   *YtildeR;               // FFT of filtered image, real part
  float   *YtildeI;               // FFT of filtered image, imag part
  float   *ZPyR;                  // zero-padded filtered image, real
  float   *ZPyI;                  // zero-padded filtered image, imag
  float   *yf;                    // float output image
  BYTE    *yb;                    // BYTE output image
  float   *fzero;                 // floating point zero image
  float   *fzero2;                // floating point zero image
```

```
printf("\nDoing Problem 2(c)...\n");
size = 256;
so2 = size/2;
Padsize = size * 2;

//
// Allocate image arrays
//
if ((xb = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((xf = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((xNb = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((xNf = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((xNhib = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((xNhif = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((GtildeCenter = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((Gf = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((G2f = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((ZPG2R = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
```

```
if ((ZPG2I = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((GtildeR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((GtildeI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((XtildeR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((XtildeI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((YtildeR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((YtildeI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((ZPxR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((ZPxI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((ZPyR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((ZPyI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((yf = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((yb = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
```

```
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((fzero = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}
if ((fzero2 = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(c).\n",cmd);
  exit(-1);
}


//
// Read images
//
disk2byte(xb,size,size,"girl2.bin");
disk2byte(xNb,size,size,"girl2Noise32.bin");
disk2byte(xNhib,size,size,"girl2Noise32Hi.bin");

//
// Cast to float
//
for (i=0; i < size*size; i++) {
  xf[i] = (float)xb[i];
  xNf[i] = (float)xNb[i];
  xNhif[i] = (float)xNhib[i];
}

//
// Make floating point zero images
//
for (i=0; i < size*size; i++) {
  fzero[i] = fzero2[i] = (float)0.0;
}

//
// Design the Gaussian LPF centered frequency response
//
U_cutoff_G = 64.0;
SigmaG = 0.19 * 256.0 / U_cutoff_G;
for (row=0; row < size; row++) {
  for (col=0; col < size; col++) {
    U = (float)(col - so2);
    V = (float)(row - so2);
    GtildeCenter[row*size + col] = (float)exp(
      (-2.0 * M_PI * M_PI * pow((double)SigmaG,(double)2.0))
        / pow((double)256.0,(double)2.0)
        * (pow((double)U,(double)2.0)
```

```
          + pow((double)V,(double)2.0)));
  }    // for col
}      // for row

//
// Invert to obtain zero-phase impulse response image
//
fft2d(Gf,fzero2,GtildeCenter,fzero,size,-1);

//
// Permute the quadrants of the zero-phase impulse response
//   image to center it
//
for (row=0; row < so2; row++) {
  for (col=0; col < so2; col++) {

    // Quadrant I
    G2f[row*size + col] = Gf[(row+so2)*size + (col+so2)];

    // Quadrant II
    G2f[row*size + (col+so2)] = Gf[(row+so2)*size + col];

    // Quadrant III
    G2f[(row+so2)*size + (col+so2)] = Gf[row*size + col];

    // Quadrant IV
    G2f[(row+so2)*size + col] = Gf[row*size + (col+so2)];

  }    // for col
}      // for row

//
// Zero pad the centered impulse response image
//
for (i=0; i < Padsize*Padsize; i++) {
  ZPG2R[i] = ZPG2I[i] = (float)0.0;
}
for (row=0; row < size; row++) {
  for (col=0; col < size; col++) {
    ZPG2R[row*Padsize + col] = G2f[row*size + col];
  }
}

//
// Compute the DFT of the zero-padded, centered impulse response
//
fft2d(ZPG2R,ZPG2I,GtildeR,GtildeI,Padsize,1);

//
```

```
// Zero pad girl2, apply filter, write to disk, compute MSE
//
for (i=0; i < Padsize*Padsize; i++) {
  ZPxR[i] = ZPxI[i] = (float)0.0;
}
for (row=0; row < size; row++) {
  for (col=0; col < size; col++) {
    ZPxR[row*Padsize + col] = xf[row*size + col];
  }
}
fft2d(ZPxR,ZPxI,XtildeR,XtildeI,Padsize,1);

for (i=0; i < Padsize*Padsize; i++) {
  fCMult(&YtildeR[i],&YtildeI[i],XtildeR[i],XtildeI[i],
                                 GtildeR[i],GtildeI[i]);
}
fft2d(ZPyR,ZPyI,YtildeR,YtildeI,Padsize,-1);
for (row=0,row2=so2; row < size; row++,row2++) {
  for (col=0,col2=so2; col < size; col++,col2++) {
    yf[row*size + col] = ZPyR[row2*Padsize + col2];
  }
}
MSE = fMSE(xf,yf,size);
printf("\nMSE:  Gaussian LPF on girl2:     %.4f",MSE);
yb = f2b_FullScale(yf,size,cmd);
byte2disk(yb,size,size,"CY2.bin");
free(yb);

//
// Zero pad girl2Noise32Hi, apply filter, write to disk, compute MSE & ISNR
//
for (i=0; i < Padsize*Padsize; i++) {
  ZPxR[i] = ZPxI[i] = (float)0.0;
}
for (row=0; row < size; row++) {
  for (col=0; col < size; col++) {
    ZPxR[row*Padsize + col] = xNhif[row*size + col];
  }
}
fft2d(ZPxR,ZPxI,XtildeR,XtildeI,Padsize,1);

for (i=0; i < Padsize*Padsize; i++) {
  fCMult(&YtildeR[i],&YtildeI[i],XtildeR[i],XtildeI[i],
                                 GtildeR[i],GtildeI[i]);
}
fft2d(ZPyR,ZPyI,YtildeR,YtildeI,Padsize,-1);
for (row=0,row2=so2; row < size; row++,row2++) {
  for (col=0,col2=so2; col < size; col++,col2++) {
    yf[row*size + col] = ZPyR[row2*Padsize + col2];
```

```
  }
}
MSE = fMSE(xf,yf,size);
printf("\nMSE:  Gaussian LPF on Noise32Hi: %.4f",MSE);
ISNR = fISNR(xf,xNhif,yf,size);
printf("\nISNR: Gaussian LPF on Noise32Hi: %.4f dB",ISNR);
yb = f2b_FullScale(yf,size,cmd);
byte2disk(yb,size,size,"CY2Nhi.bin");
free(yb);

//
// Zero pad girl2Noise32, apply filter, write to disk, compute MSE & ISNR
//
for (i=0; i < Padsize*Padsize; i++) {
  ZPxR[i] = ZPxI[i] = (float)0.0;
}
for (row=0; row < size; row++) {
  for (col=0; col < size; col++) {
    ZPxR[row*Padsize + col] = xNf[row*size + col];
  }
}
fft2d(ZPxR,ZPxI,XtildeR,XtildeI,Padsize,1);

for (i=0; i < Padsize*Padsize; i++) {
  fCMult(&YtildeR[i],&YtildeI[i],XtildeR[i],XtildeI[i],
                                 GtildeR[i],GtildeI[i]);
}
fft2d(ZPyR,ZPyI,YtildeR,YtildeI,Padsize,-1);
for (row=0,row2=so2; row < size; row++,row2++) {
  for (col=0,col2=so2; col < size; col++,col2++) {
    yf[row*size + col] = ZPyR[row2*Padsize + col2];
  }
}
MSE = fMSE(xf,yf,size);
printf("\nMSE:  Gaussian LPF on Noise32:   %.4f",MSE);
ISNR = fISNR(xf,xNf,yf,size);
printf("\nISNR: Gaussian LPF on Noise32:   %.4f dB\n",ISNR);
yb = f2b_FullScale(yf,size,cmd);
byte2disk(yb,size,size,"CY2N.bin");
free(yb);

//
// Collect the garbage
//
free(xb);
free(xf);
free(yf);
free(Gf);
free(G2f);
```

```
  free(xNb);
  free(xNf);
  free(ZPxR);
  free(ZPxI);
  free(ZPyR);
  free(ZPyI);
  free(ZPG2R);
  free(ZPG2I);
  free(xNhib);
  free(xNhif);
  free(fzero);
  free(fzero2);
  free(GtildeR);
  free(GtildeI);
  free(XtildeR);
  free(XtildeI);
  free(YtildeR);
  free(YtildeI);

  return;
} /*---------------------  Problem2c  ---------------------------------*/

/*----------------------------------------------------------------------
 * Problem2d
 *
 *   HW 5, Problem 2(d)
 *
 *   Read images:
 *     - girl2.bin
 *     - girl2Noise32Hi.bin
 *     - girl2Noise32.bin
 *
 *  Use the method of Example 4 on page 5.65 of the course notes
 *  to apply a Gaussian LPF with U_cutoff = 77.5 cpi.
 *
 *  jph 25 March 2017
 *
 -----------------------------------------------------------------------*/

void Problem2d(cmd)

  char    *cmd;                   // command used to invoke this program
{

  int      i;                     // loop counter
  int      size;                  // num rows/cols in input image
  int      so2;                   // size/2
  int      Padsize;               // size for zero padded images
  int      row;                   // row counter
```

```
int      col;                   // col counter
int      row2;                  // row counter
int      col2;                  // col counter
float    MSE;                   // mean squared error
float    ISNR;                  // improvement in SNR
float    U_cutoff_G;            // LPF cutoff frequency in cpi
float    SigmaG;                // Gaussian filter space constant
float    U;                     // horiz freq in cpi
float    V;                     // vert  freq in cpi
BYTE    *xb;                    // BYTE  image: girl2.bin
float   *xf;                    // float image: girl2.bin
BYTE    *xNb;                   // BYTE  image: girl2Noise32.bin
float   *xNf;                   // float image: girl2Noise32.bin
BYTE    *xNhib;                 // BYTE  image: girl2Noise32Hi.bin
float   *xNhif;                 // float image: girl2Noise32Hi.bin
float   *GtildeCenter;          // centered frequency response image
float   *Gf;                    // zero-phase impulse response image
float   *G2f;                   // centered impulse response image
float   *ZPG2R;                 // zero-padded G2 image, real part
float   *ZPG2I;                 // zero-padded G2 image, imag part
float   *GtildeR;               // FFT of ZPG2, real part
float   *GtildeI;               // FFT of ZPG2, imag part
float   *ZPxR;                  // zero padded input image, real part
float   *ZPxI;                  // zero padded input image, imag part
float   *XtildeR;               // FFT of ZPx, imag part
float   *XtildeI;               // FFT of ZPx, imag part
float   *YtildeR;               // FFT of filtered image, real part
float   *YtildeI;               // FFT of filtered image, imag part
float   *ZPyR;                  // zero-padded filtered image, real
float   *ZPyI;                  // zero-padded filtered image, imag
float   *yf;                    // float output image
BYTE    *yb;                    // BYTE output image
float   *fzero;                 // floating point zero image
float   *fzero2;                // floating point zero image

printf("\nDoing Problem 2(d)...\n");
size = 256;
so2 = size/2;
Padsize = size * 2;

//
// Allocate image arrays
//
if ((xb = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
  exit(-1);
}
if ((xf = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
```

```
    exit(-1);
  }
  if ((xNb = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
    exit(-1);
  }
  if ((xNf = (float*)malloc(size*size*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
    exit(-1);
  }
  if ((xNhib = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
    exit(-1);
  }
  if ((xNhif = (float*)malloc(size*size*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
    exit(-1);
  }
  if ((GtildeCenter = (float*)malloc(size*size*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
    exit(-1);
  }
  if ((Gf = (float*)malloc(size*size*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
    exit(-1);
  }
  if ((G2f = (float*)malloc(size*size*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
    exit(-1);
  }
  if ((ZPG2R = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
    exit(-1);
  }
  if ((ZPG2I = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
    exit(-1);
  }
  if ((GtildeR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
    exit(-1);
  }
  if ((GtildeI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
    exit(-1);
  }
  if ((XtildeR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
    printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
    exit(-1);
```

```
}
if ((XtildeI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
  exit(-1);
}
if ((YtildeR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
  exit(-1);
}
if ((YtildeI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
  exit(-1);
}
if ((ZPxR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
  exit(-1);
}
if ((ZPxI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
  exit(-1);
}
if ((ZPyR = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
  exit(-1);
}
if ((ZPyI = (float*)malloc(Padsize*Padsize*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
  exit(-1);
}
if ((yf = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
  exit(-1);
}
if ((yb = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
  exit(-1);
}
if ((fzero = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
  exit(-1);
}
if ((fzero2 = (float*)malloc(size*size*sizeof(float))) == NULL) {
  printf("\n%s: free store exhausted in Problem 2(d).\n",cmd);
  exit(-1);
}


//
// Read images
```

```
//
disk2byte(xb,size,size,"girl2.bin");
disk2byte(xNb,size,size,"girl2Noise32.bin");
disk2byte(xNhib,size,size,"girl2Noise32Hi.bin");

//
// Cast to float
//
for (i=0; i < size*size; i++) {
  xf[i] = (float)xb[i];
  xNf[i] = (float)xNb[i];
  xNhif[i] = (float)xNhib[i];
}

//
// Make floating point zero images
//
for (i=0; i < size*size; i++) {
  fzero[i] = fzero2[i] = (float)0.0;
}

//
// Design the Gaussian LPF centered frequency response
//
U_cutoff_G = 77.5;
SigmaG = 0.19 * 256.0 / U_cutoff_G;
for (row=0; row < size; row++) {
  for (col=0; col < size; col++) {
    U = (float)(col - so2);
    V = (float)(row - so2);
    GtildeCenter[row*size + col] = (float)exp(
      (-2.0 * M_PI * M_PI * pow((double)SigmaG,(double)2.0))
        / pow((double)256.0,(double)2.0)
        * (pow((double)U,(double)2.0)
          + pow((double)V,(double)2.0)));
  }    // for col
}      // for row

//
// Invert to obtain zero-phase impulse response image
//
fft2d(Gf,fzero2,GtildeCenter,fzero,size,-1);

//
// Permute the quadrants of the zero-phase impulse response
//   image to center it
//
for (row=0; row < so2; row++) {
  for (col=0; col < so2; col++) {
```

```
    // Quadrant I
    G2f[row*size + col] = Gf[(row+so2)*size + (col+so2)];

    // Quadrant II
    G2f[row*size + (col+so2)] = Gf[(row+so2)*size + col];

    // Quadrant III
    G2f[(row+so2)*size + (col+so2)] = Gf[row*size + col];

    // Quadrant IV
    G2f[(row+so2)*size + col] = Gf[row*size + (col+so2)];

  }    // for col
}      // for row

//
// Zero pad the centered impulse response image
//
for (i=0; i < Padsize*Padsize; i++) {
  ZPG2R[i] = ZPG2I[i] = (float)0.0;
}
for (row=0; row < size; row++) {
  for (col=0; col < size; col++) {
    ZPG2R[row*Padsize + col] = G2f[row*size + col];
  }
}

//
// Compute the DFT of the zero-padded, centered impulse response
//
fft2d(ZPG2R,ZPG2I,GtildeR,GtildeI,Padsize,1);

//
// Zero pad girl2, apply filter, write to disk, compute MSE
//
for (i=0; i < Padsize*Padsize; i++) {
  ZPxR[i] = ZPxI[i] = (float)0.0;
}
for (row=0; row < size; row++) {
  for (col=0; col < size; col++) {
    ZPxR[row*Padsize + col] = xf[row*size + col];
  }
}
fft2d(ZPxR,ZPxI,XtildeR,XtildeI,Padsize,1);

for (i=0; i < Padsize*Padsize; i++) {
  fCMult(&YtildeR[i],&YtildeI[i],XtildeR[i],XtildeI[i],
                                 GtildeR[i],GtildeI[i]);
```

```
}
fft2d(ZPyR,ZPyI,YtildeR,YtildeI,Padsize,-1);
for (row=0,row2=so2; row < size; row++,row2++) {
  for (col=0,col2=so2; col < size; col++,col2++) {
    yf[row*size + col] = ZPyR[row2*Padsize + col2];
  }
}
MSE = fMSE(xf,yf,size);
printf("\nMSE:  Gaussian2 LPF on girl2:     %.4f",MSE);
yb = f2b_FullScale(yf,size,cmd);
byte2disk(yb,size,size,"CY3.bin");
free(yb);

//
// Zero pad girl2Noise32Hi, apply filter, write to disk, compute MSE & ISNR
//
for (i=0; i < Padsize*Padsize; i++) {
  ZPxR[i] = ZPxI[i] = (float)0.0;
}
for (row=0; row < size; row++) {
  for (col=0; col < size; col++) {
    ZPxR[row*Padsize + col] = xNhif[row*size + col];
  }
}
fft2d(ZPxR,ZPxI,XtildeR,XtildeI,Padsize,1);

for (i=0; i < Padsize*Padsize; i++) {
  fCMult(&YtildeR[i],&YtildeI[i],XtildeR[i],XtildeI[i],
                                 GtildeR[i],GtildeI[i]);
}
fft2d(ZPyR,ZPyI,YtildeR,YtildeI,Padsize,-1);
for (row=0,row2=so2; row < size; row++,row2++) {
  for (col=0,col2=so2; col < size; col++,col2++) {
    yf[row*size + col] = ZPyR[row2*Padsize + col2];
  }
}
MSE = fMSE(xf,yf,size);
printf("\nMSE:  Gaussian2 LPF on Noise32Hi: %.4f",MSE);
ISNR = fISNR(xf,xNhif,yf,size);
printf("\nISNR: Gaussian2 LPF on Noise32Hi: %.4f dB",ISNR);
yb = f2b_FullScale(yf,size,cmd);
byte2disk(yb,size,size,"CY3Nhi.bin");
free(yb);

//
// Zero pad girl2Noise32, apply filter, write to disk, compute MSE & ISNR
//
for (i=0; i < Padsize*Padsize; i++) {
  ZPxR[i] = ZPxI[i] = (float)0.0;
```

```
}
for (row=0; row < size; row++) {
  for (col=0; col < size; col++) {
    ZPxR[row*Padsize + col] = xNf[row*size + col];
  }
}
fft2d(ZPxR,ZPxI,XtildeR,XtildeI,Padsize,1);

for (i=0; i < Padsize*Padsize; i++) {
  fCMult(&YtildeR[i],&YtildeI[i],XtildeR[i],XtildeI[i],
                               GtildeR[i],GtildeI[i]);
}
fft2d(ZPyR,ZPyI,YtildeR,YtildeI,Padsize,-1);
for (row=0,row2=so2; row < size; row++,row2++) {
  for (col=0,col2=so2; col < size; col++,col2++) {
    yf[row*size + col] = ZPyR[row2*Padsize + col2];
  }
}
MSE = fMSE(xf,yf,size);
printf("\nMSE:  Gaussian2 LPF on Noise32:   %.4f",MSE);
ISNR = fISNR(xf,xNf,yf,size);
printf("\nISNR: Gaussian2 LPF on Noise32:   %.4f dB\n",ISNR);
yb = f2b_FullScale(yf,size,cmd);
byte2disk(yb,size,size,"CY3N.bin");
free(yb);

//
// Collect the garbage
//
free(xb);
free(xf);
free(yf);
free(Gf);
free(G2f);
free(xNb);
free(xNf);
free(ZPxR);
free(ZPxI);
free(ZPyR);
free(ZPyI);
free(ZPG2R);
free(ZPG2I);
free(xNhib);
free(xNhif);
free(fzero);
free(fzero2);
free(GtildeR);
free(GtildeI);
free(XtildeR);
```

```
  free(XtildeI);
  free(YtildeR);
  free(YtildeI);

  return;
} /*---------------------  Problem2d  ---------------------------------*/

/*-----------------------------------------------------------------------
 * disk2byte.c
 *
 *   function reads an unsigned char (byte) image from disk
 *
 *
 *  jph 15 June 1992
 *
 ------------------------------------------------------------------------*/

void disk2byte(x,row_dim,col_dim,fn)

  BYTE    *x;             /* image to be read */
  int     row_dim;        /* row dimension of x */
  int     col_dim;        /* col dimension of x */
  char   *fn;             /* filename */
{

  int fd;               /* file descriptor */
  int n_bytes;          /* number of bytes to read */

 /*
  * detect zero dimension input
  */
  if ((row_dim==0) || (col_dim==0)) return;

 /*
  * create and open the file
  */
  if ((fd = open(fn, O_RDONLY))==-1) {
    printf("\ndisk2byte.c : could not open %s !",fn);
    return;
  }

 /*
  * read image data from the file
  */
  n_bytes = row_dim * col_dim * sizeof(unsigned char);
  if (read(fd,x,n_bytes) != n_bytes) {
    printf("\ndisk2byte.c : complete read of %s did not succeed.",fn);
  }
```

```
 /*
  * close file and return
  */
  if (close(fd) == -1) printf("\ndisk2byte.c : error closing %s.",fn);
  return;
} /*------------------------  disk2byte  --------------------------------*/

/*--------------------------------------------------------------------
 * byte2disk.c
 *
 *   function writes an unsigned char (byte) image to disk
 *
 *
 *  jph 15 June 1992
 *
 ----------------------------------------------------------------------*/

void byte2disk(x,row_dim,col_dim,fn)

  BYTE  *x;              /* image to be written */
  int   row_dim;         /* row dimension of x */
  int   col_dim;         /* col dimension of x */
  char *fn;              /* filename */
{

  int fd;               /* file descriptor */
  int n_bytes;          /* number of bytes to read */

 /*
  * detect zero dimension input
  */
  if ((row_dim==0) || (col_dim==0)) return;

 /*
  * create and open the file
  */
  if ((fd = open(fn, O_WRONLY | O_CREAT | O_TRUNC, 0644))==-1) {
    printf("\nbyte2disk.c : could not open %s !",fn);
    return;
  }

 /*
  * write image data to the file
  */
  n_bytes = row_dim * col_dim * sizeof(unsigned char);
  if (write(fd,x,n_bytes) != n_bytes) {
    printf("\nbyte2disk.c : complete write of %s did not succeed.",fn);
  }
```

```
 /*
  * close file and return
  */
  if (close(fd) == -1) printf("\nbyte2disk.c : error closing %s.",fn);
  return;
} /*------------------------  byte2disk  --------------------------------*/

/*-------------------------------------------------------------------
 * f2b_FullScale
 *
 *   Convert a float image to a BYTE image with full-scale contrast.
 *
 *
 *  jph 13 November 2000
 *
 ---------------------------------------------------------------------*/


BYTE *f2b_FullScale(x,size,cmd)

  float   *x;                   /* input float image */
  int      size;                /* num rows/cols in input image x */
  char    *cmd;                 /* command used to invoke this program */
{

  int      i;                   /* loop counter */
  int      N;                   /* size * size */
  float    min;                 /* minimum pixel value in input image */
  float    max;                 /* maximum pixel value in input image */
  float    ScaleFact;           /* dynamic range scale factor */
  BYTE    *y;                   /* output BYTE image */

  N = size * size;

 /*
  * Allocate output BYTE image on the heap
  */
  if ((y = (BYTE*)malloc(size*size*sizeof(BYTE))) == NULL) {
    printf("\nFree store exhausted in f2b_FullScale.\n");
    exit(-1);
  }

 /*
  * find min and max pixel values in input image
  */
  min = max = x[0];
  for (i=0; i < N; i++) {
    if (x[i] < min) {
      min = x[i];
```

```
    } else {
      if (x[i] > max) {
        max = x[i];
      }
    }
  }

 /*
  * Do full-scale contrast stretch and cast image into BYTE
  */
  ScaleFact = (float)255.0 / (max - min);
  for (i=0; i < N; i++) {
    y[i] = (BYTE)round(ScaleFact * (x[i] - min));
  }

  return(y);
} /*---------------------  f2b_FullScale  -----------------------------*/

/*
 * fft2d.c
 *
 *  Function implements the 2D FFT.  FFTW3 is called to compute the FFT.
 *  The frequency domain coordinates are as described in the FFT handout
 *  given out in class.  FFTW3 must be installed for this routine to work.
 *
 *    The image must be square and the row/col dimension must be even.
 *
 *    If you want to cut this routine and put it in a separate file so
 *    that you can compile it separately from the main() and then link to
 *    it, you need to #include "fftw3.h" and link -lfftw3 -lm.
 *
 *  2/28/07 jph
 *
 */

void fft2d(xReal,xImag,XReal,XImag,size,direction)

  float *xReal;       /* real part of signal */
  float *xImag;       /* imaginary part of signal */
  float *XReal;       /* real part of spectrum */
  float *XImag;       /* imaginary part of spectrum */
  int    size;        /* row/col dim of image */
  int    direction;   /* 1=fwd xform, -1=inverse xform */

{
    fftw_complex *pass;           /* array for passing data to/from fftw */
    fftw_plan Plan;               /* structure for fftw3 planning */
    float one_on_n;               /* 1 / (no. data points in signal) */
    int i;                        /* counter */
```

```
int n;                         /* no. data points in signal */
int so2;                       /* size over 2 */
int row,col;                   /* loop counters */

n = size * size;
so2 = (size >> 1);
pass  = fftw_malloc(n*sizeof(fftw_complex));

if (direction == 1 ) { /* forward transform */
  Plan = fftw_plan_dft_2d(size,size,pass,pass,FFTW_FORWARD,FFTW_ESTIMATE);
 /*
  * Set up the data in the pass array and call fftw3
  */
  for (i=0; i<n; i++) {
    pass[i][0] = xReal[i];
    pass[i][1] = xImag[i];
  }
  fftw_execute(Plan);

 /*
  * Center the spectrum returned by fftw3
  */
  for (row=0; row<so2; row++) {
    for (col=0; col<so2; col++) {

      // Quadrant I
      XReal[(row+so2)*size + col+so2] = pass[row*size + col][0];
      XImag[(row+so2)*size + col+so2] = pass[row*size + col][1];

      // Quadrant II
      XReal[(row+so2)*size + col] = pass[row*size + col+so2][0];
      XImag[(row+so2)*size + col] = pass[row*size + col+so2][1];

      // Quadrant III
      XReal[row*size + col] = pass[(row+so2)*size + col+so2][0];
      XImag[row*size + col] = pass[(row+so2)*size + col+so2][1];

      // Quadrant IV
      XReal[row*size + col+so2] = pass[(row+so2)*size + col][0];
      XImag[row*size + col+so2] = pass[(row+so2)*size + col][1];

    }    // for col
  }      // for row
}        // if (direction == 1)

else {
  if (direction == -1) { /* reverse transform */
    Plan = fftw_plan_dft_2d(size,size,pass,pass,FFTW_BACKWARD,FFTW_ESTIMATE);
    one_on_n = (float)1.0 / (float)n;
```

```
      /*
       * "un" Center the given spectrum for passing to fftw3
       */
       for (row=0; row<so2; row++) {
         for (col=0; col<so2; col++) {

           // Quadrant I
           pass[row*size + col][0] = XReal[(row+so2)*size + col+so2];
           pass[row*size + col][1] = XImag[(row+so2)*size + col+so2];

           // Quadrant II
           pass[row*size + col+so2][0] = XReal[(row+so2)*size + col];
           pass[row*size + col+so2][1] = XImag[(row+so2)*size + col];

           // Quadrant III
           pass[(row+so2)*size + col+so2][0] = XReal[row*size + col];
           pass[(row+so2)*size + col+so2][1] = XImag[row*size + col];

           // Quadrant IV
           pass[(row+so2)*size + col][0] = XReal[row*size + col+so2];
           pass[(row+so2)*size + col][1] = XImag[row*size + col+so2];

         }    // for col
       }      // for row

       fftw_execute(Plan);

      /*
       * Copy data back out of pass array and scale
       */
       for (i=0; i<n; i++) {
         xReal[i] = pass[i][0] * one_on_n;
         xImag[i] = pass[i][1] * one_on_n;
       }
     }    // else

     else {
       printf("\nERROR: fft2d: unknown value %d specified for direction.\n",
              direction);
       exit(-1);
     }
   }
   fftw_destroy_plan(Plan);
   fftw_free(pass);
   return;
} /*----------------------------  fft2d  ---------------------------------*/

/*----------------------------------------------------------------------
```

```
 * L2Norm
 *
 *   Return the L2 norm (Euclidean norm) of a floating point 2-vector.
 *
 *  jph 13 November 2000
 *
 ------------------------------------------------------------------------*/

float L2Norm(x,y)

  float      x;                   /* first element of input vector */
  float      y;                   /* second element of input vector */
{

  return((float)pow(
             pow((double)x,(double)2.0) + pow((double)y,(double)2.0),
                                                (double)0.5));

} /*---------------------  L2Norm --------------------------------------*/

/*-----------------------------------------------------------------------
 * fCMult.c
 *
 *   Function computes a float complex product.  Output (yReal, yImag) is
 *   set equal to the product of the inputs (aReal,aImag) * (bReal,bImag).
 *
 *  jph 9/13/93
 ------------------------------------------------------------------------*/

void fCMult(yReal,yImag,aReal,aImag,bReal,bImag)

  float *yReal;    /* pointer to real part of product */
  float *yImag;    /* pointer to imag part of product */
  float  aReal;    /* real part of multiplicand */
  float  aImag;    /* imag part of multiplicand */
  float  bReal;    /* real part of multiplier */
  float  bImag;    /* imag part of multiplier */

{
  *yReal = (aReal * bReal) - (aImag * bImag);
  *yImag = (aReal * bImag) + (aImag * bReal);
  return;
} /*---------------------  fCMult --------------------------------------*/

/*-----------------------------------------------------------------------
 * PrintMaxDiffB
 *
 *   Print out the max abs difference between two BYTE images.
 *
```

```
 *
 *  jph 25 March 2017
 *
 -------------------------------------------------------------------------*/


void PrintMaxDiffB(x1,x2,size,p1,p2)

  BYTE    *x1;                     // BYTE image from part p1
  BYTE    *x2;                     // BYTE image from part p2
  int      size;                   // num rows/cols in input image x
  char     p1;                     // letter designation of x1 part
  char     p2;                     // letter designation of x2 part
{

  int      i;                      // loop counter
  float    Dif;                    // float difference btwn two pixels
  float    MaxDif;                 // max abs difference between x1 and x2

  //
  // Loop over pixels; find the max abs diff between x1 and x2
  //
  MaxDif = (float)0.0;
  for (i=0; i < size*size; i++) {
    Dif = fabsf((float)x1[i] - (float)x2[i]);
    if (Dif > MaxDif) {
      MaxDif = Dif;
    }
  }

  //
  // Print result
  //
  printf("\n(%c): max difference from part (%c): %.2f\n",p1,p2,MaxDif);

  return;
} /*--------------------  PrintMAxDiffB  -----------------------------*/

/*-----------------------------------------------------------------------
 * fMSE
 *
 *   Compute MSE between two float images.
 *
 *
 *  jph 25 March 2017
 *
 -------------------------------------------------------------------------*/

float fMSE(x1,x2,size)
```

```
  float   *x1;                    // float input image
  float   *x2;                    // float input image
  int      size;                  // num rows/cols in input images
{

  int      i;                     // loop counter
  double   MSE;                   // mean squared error

  //
  // Compute MSE
  //
  MSE = (double)0.0;
  for (i=0; i < size*size; i++) {
    MSE += pow((double)(x1[i]-x2[i]),(double)2.0);
  }
  MSE = MSE / (double)(size*size);

  return((float)MSE);
} /*---------------------  fMSE  ---------------------------------------*/

/*----------------------------------------------------------------------
 * fISNR
 *
 *   Compute ISNR for a floating point filtering operation
 *
 *
 *  jph 25 March 2017
 *
 -----------------------------------------------------------------------*/

float fISNR(x1,x2,y,size)

  float   *x1;                    // original image
  float   *x2;                    // corrupted image
  float   *y;                     // filtered image
  int      size;                  // num rows/cols in input images
{

  return((float)((double)10.0 *
          log10((double)fMSE(x1,x2,size)/(double)fMSE(x1,y,size))));

} /*---------------------  fISNR  --------------------------------------*/
```