DIGITAL IMAGE PROCESSING

Image Enhancement:
Filtering in the Frequency Domain

Contents

In this lecture we will look at image enhancement in the frequency domain

- Jean Baptiste Joseph Fourier
- The Fourier series & the Fourier transform
- Image Processing in the frequency domain
  - Image smoothing
  - Image sharpening
- Fast Fourier Transform

Jean Baptiste Joseph Fourier

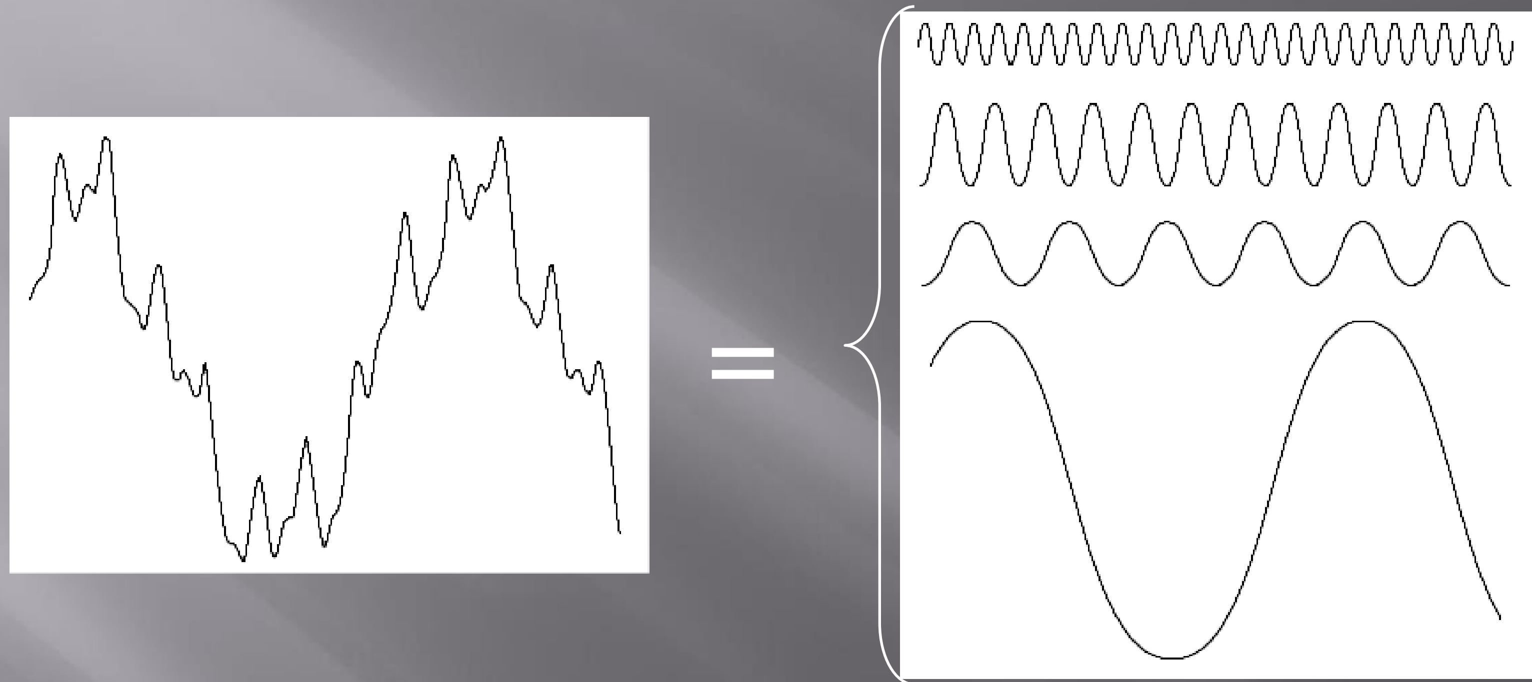
Fourier was born in Auxerre, France in 1768

- Most famous for his work *"La Théorie Analitique de la Chaleur"* published in 1822
- Translated into English in 1878: *"The Analytic Theory of Heat"*

uch attention when the work was first published

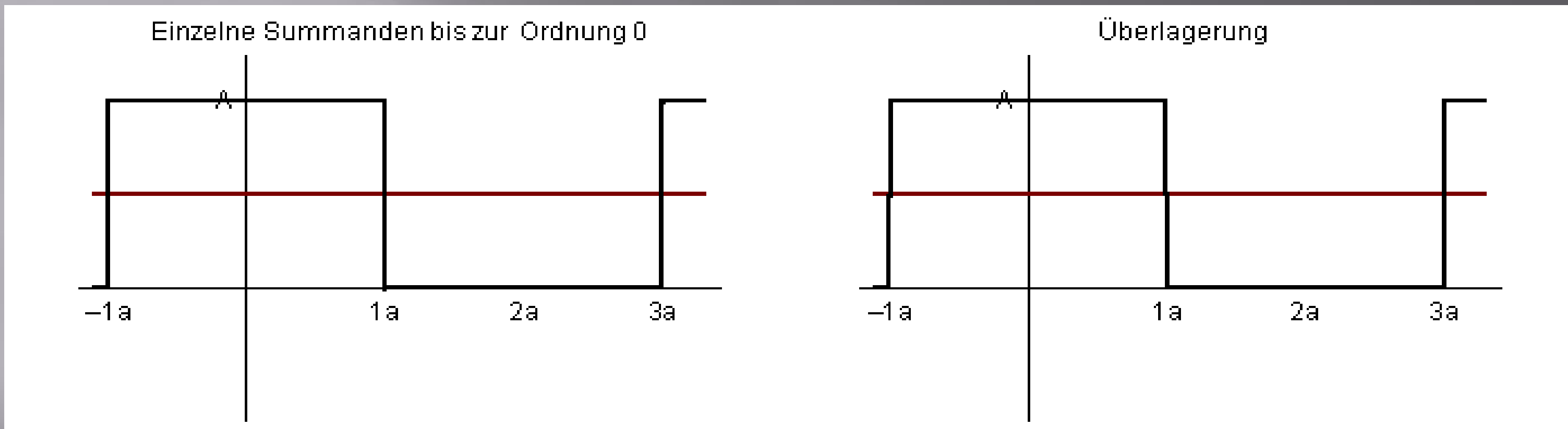
One of the most important mathematical theories in modern engineering

The Big Idea



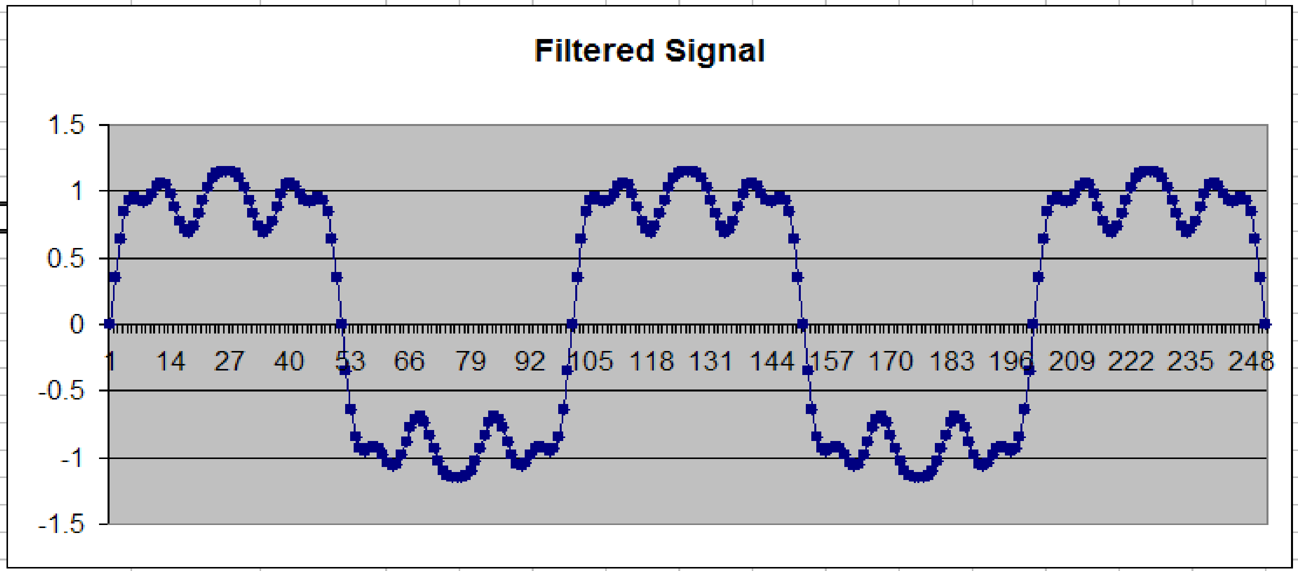
Any function that periodically repeats itself can be expressed as a sum of sines and cosines of different frequencies each multiplied by a different coefficient – a *Fourier series*

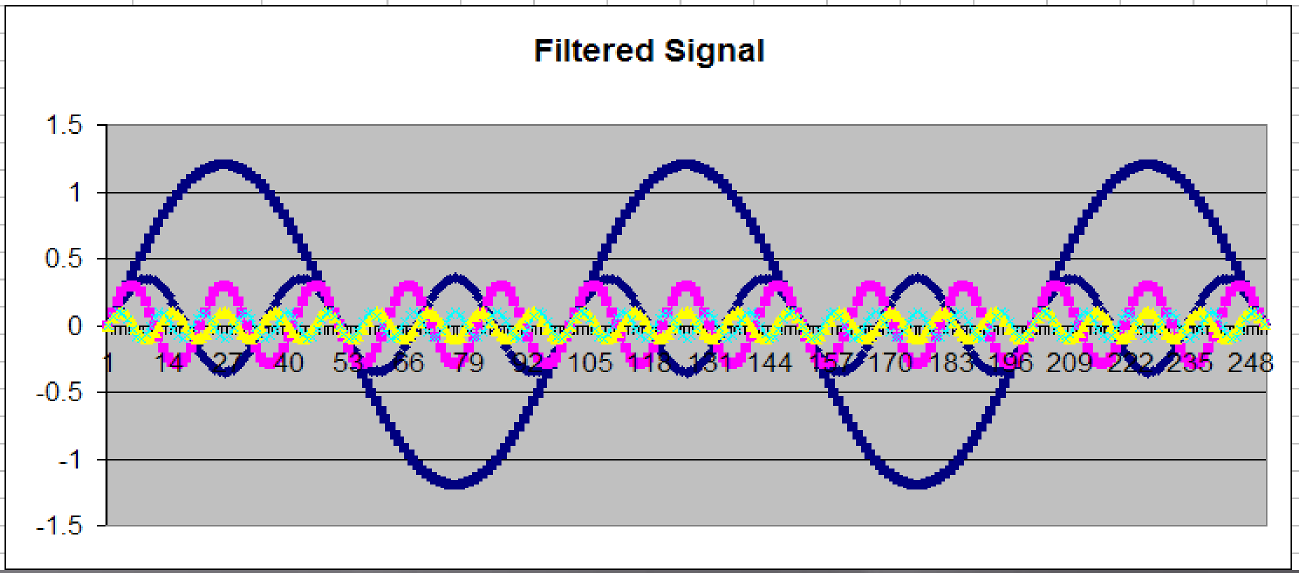
The Big Idea (cont…)



Notice how we get closer and closer to the original function as we add more and more frequencies

The Big Idea (cont…)





Frequency domain signal processing example in Excel

The Discrete Fourier Transform (DFT)

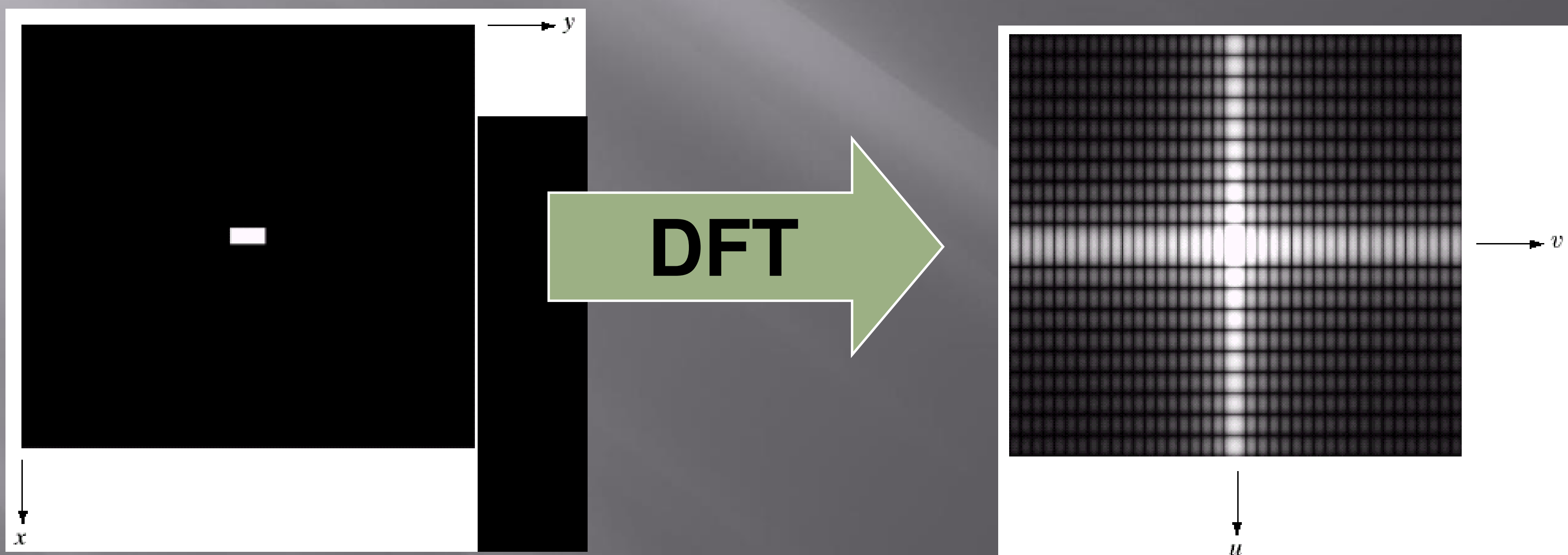
The *Discrete Fourier Transform* of *f(x, y)*, for $x = 0, 1, 2 \ldots M-1$ and $y = 0,1,2 \ldots N-1$, denoted by *F(u, v)*, is given by the equation:

$$F(u,v) = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x,y) e^{-j2\pi(ux/M + vy/N)}$$

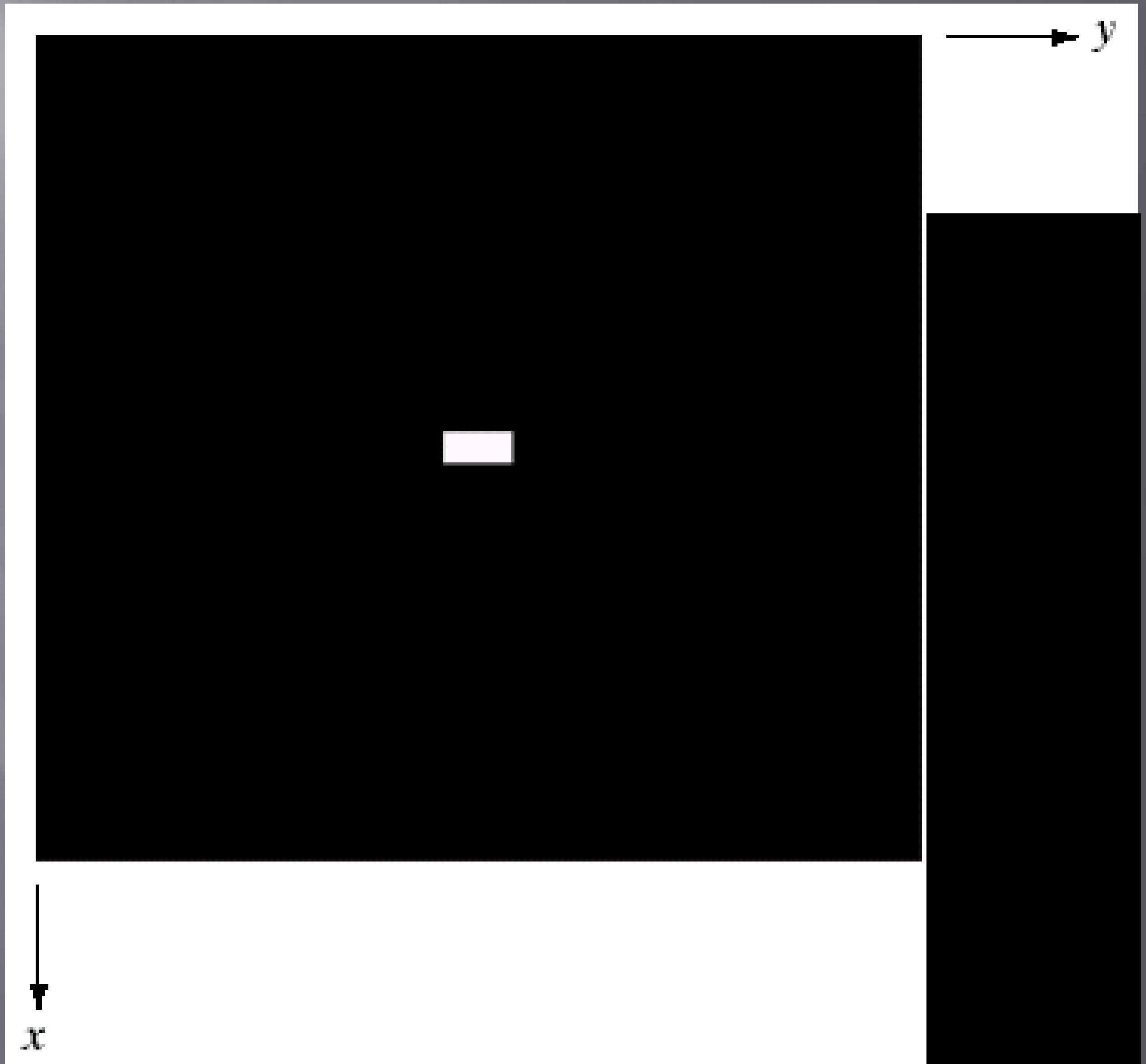
for $u = 0, 1, 2 \ldots M-1$ and $v = 0, 1, 2 \ldots N-1$.

DFT & Images

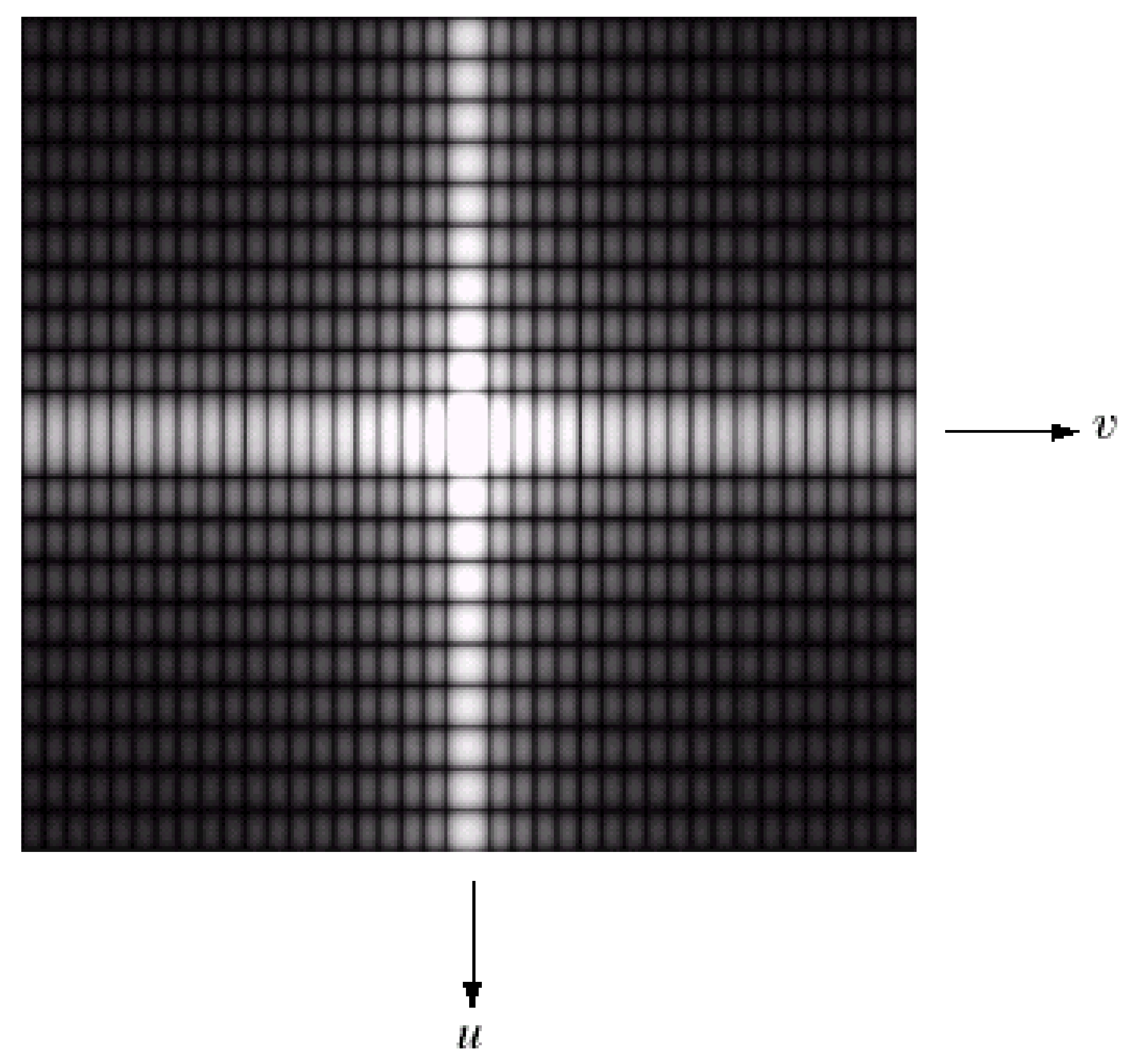
The DFT of a two dimensional image can be visualised by showing the spectrum of the images component frequencies



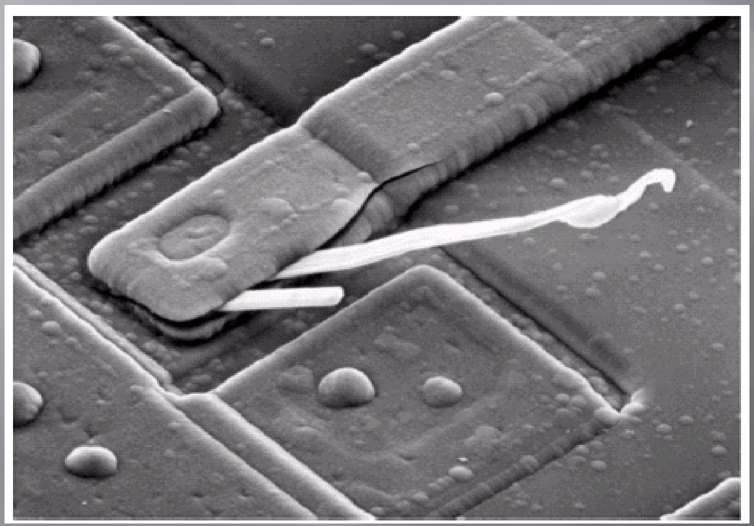
DFT & Images



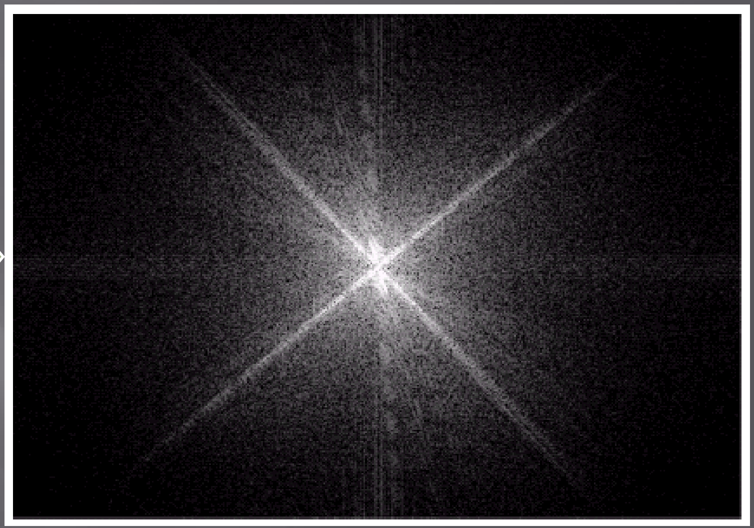
DFT & Images



DFT & Images (cont…)

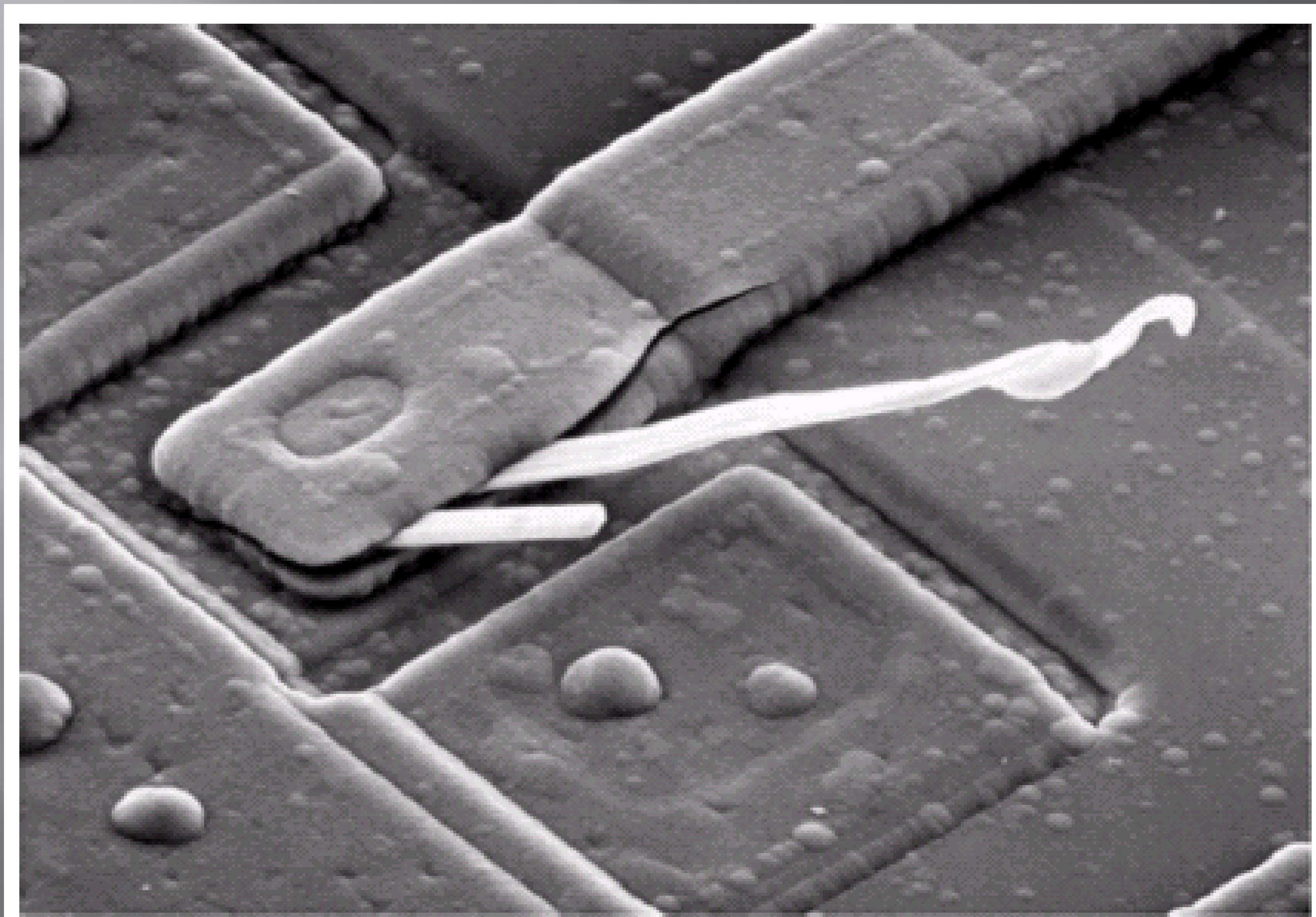


Scanning electron microscope image of an integrated circuit magnified ~2500 times

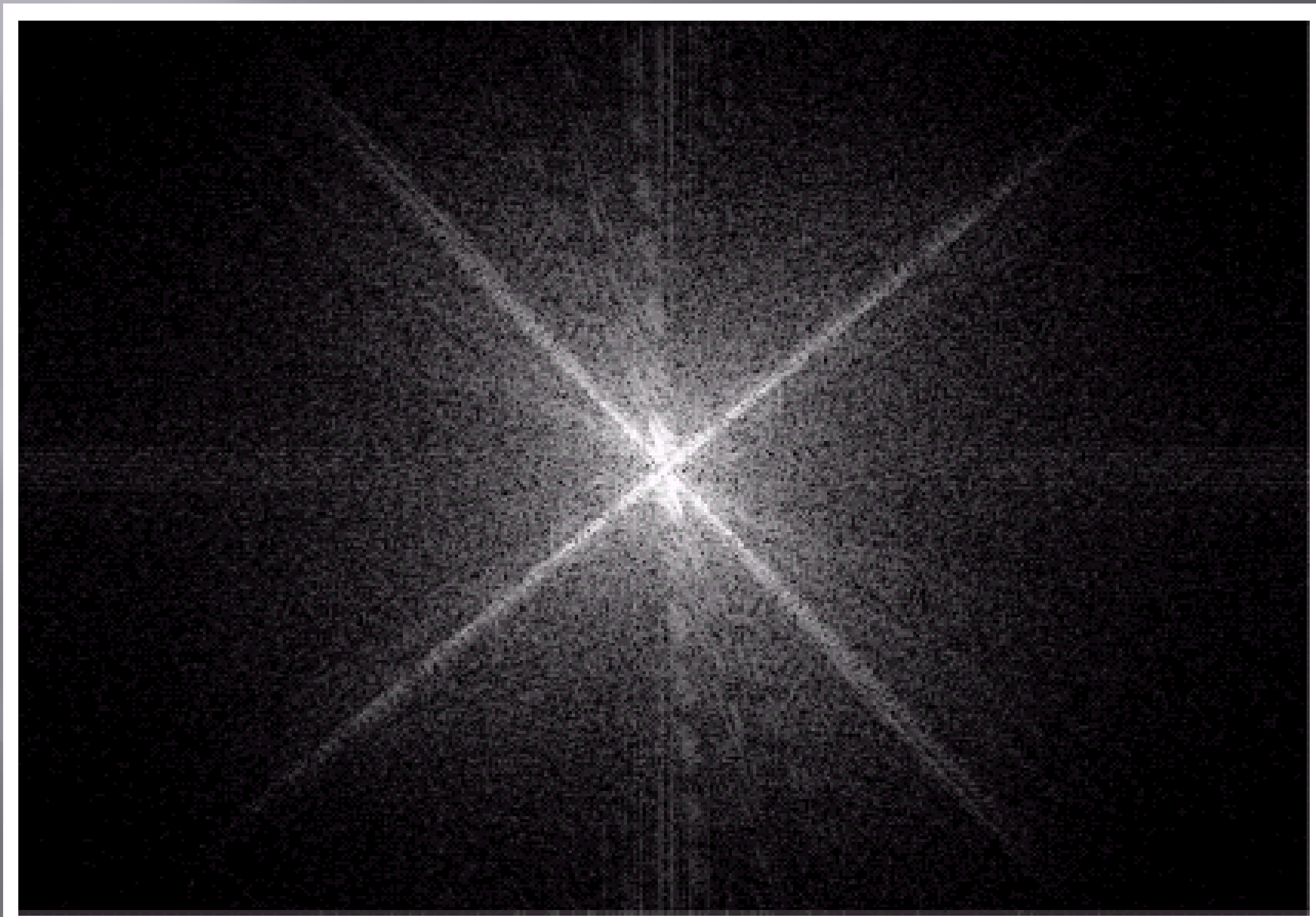


Fourier spectrum of the image

DFT & Images (cont…)



DFT & Images (cont…)



The Inverse DFT

It is really important to note that the Fourier transform is completely **reversible**

The inverse DFT is given by:

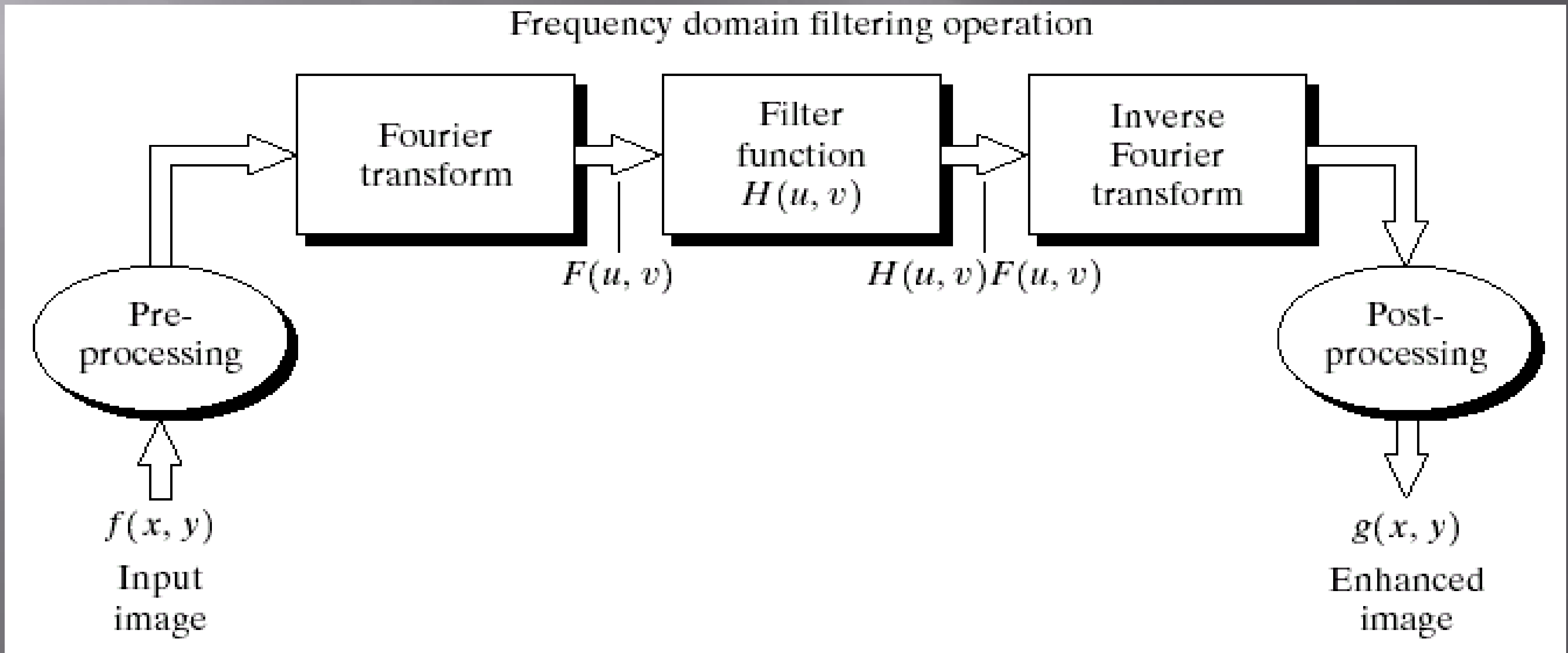
$$f(x,y) = \frac{1}{MN} \sum_{u=0}^{M-1} \sum_{v=0}^{N-1} F(u,v) e^{j2\pi(ux/M + vy/N)}$$

for x = 0, 1, 2…M-1 and y = 0, 1, 2…N-1

The DFT and Image Processing

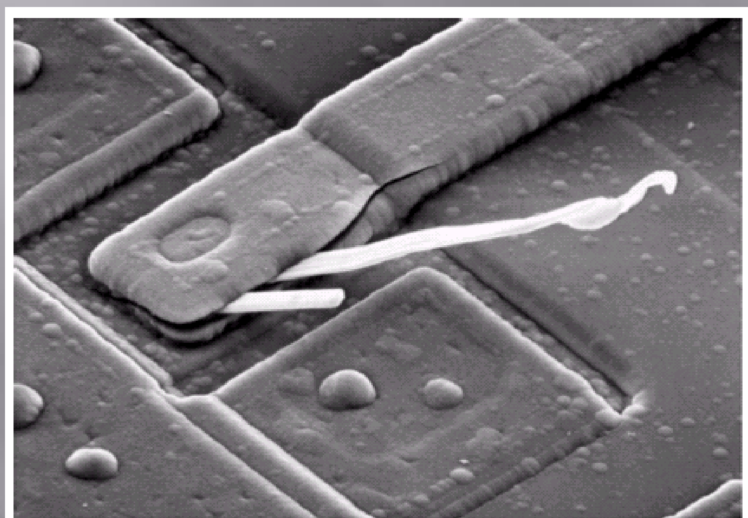
To filter an image in the frequency domain:

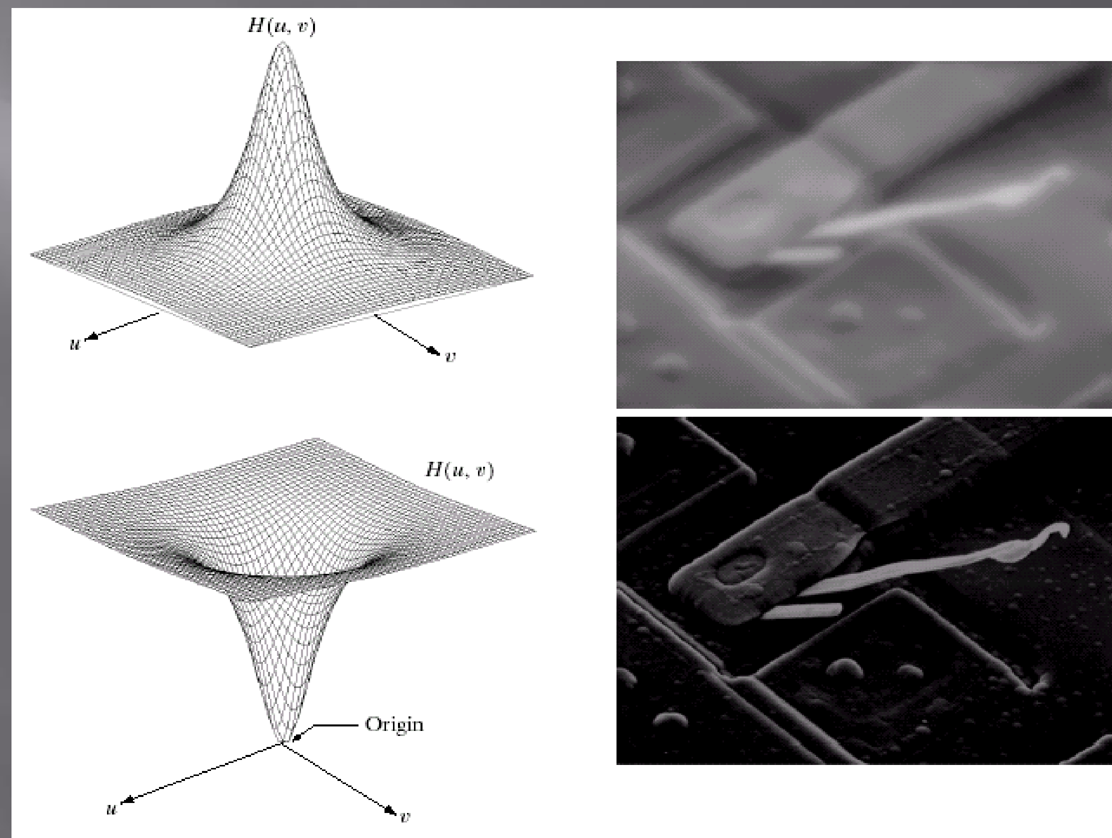
1. Compute *F(u,v)* the DFT of the image
2. Multiply *F(u,v)* by a filter function *H(u,v)*
3. Compute the inverse DFT of the result



Some Basic Frequency Domain Filters

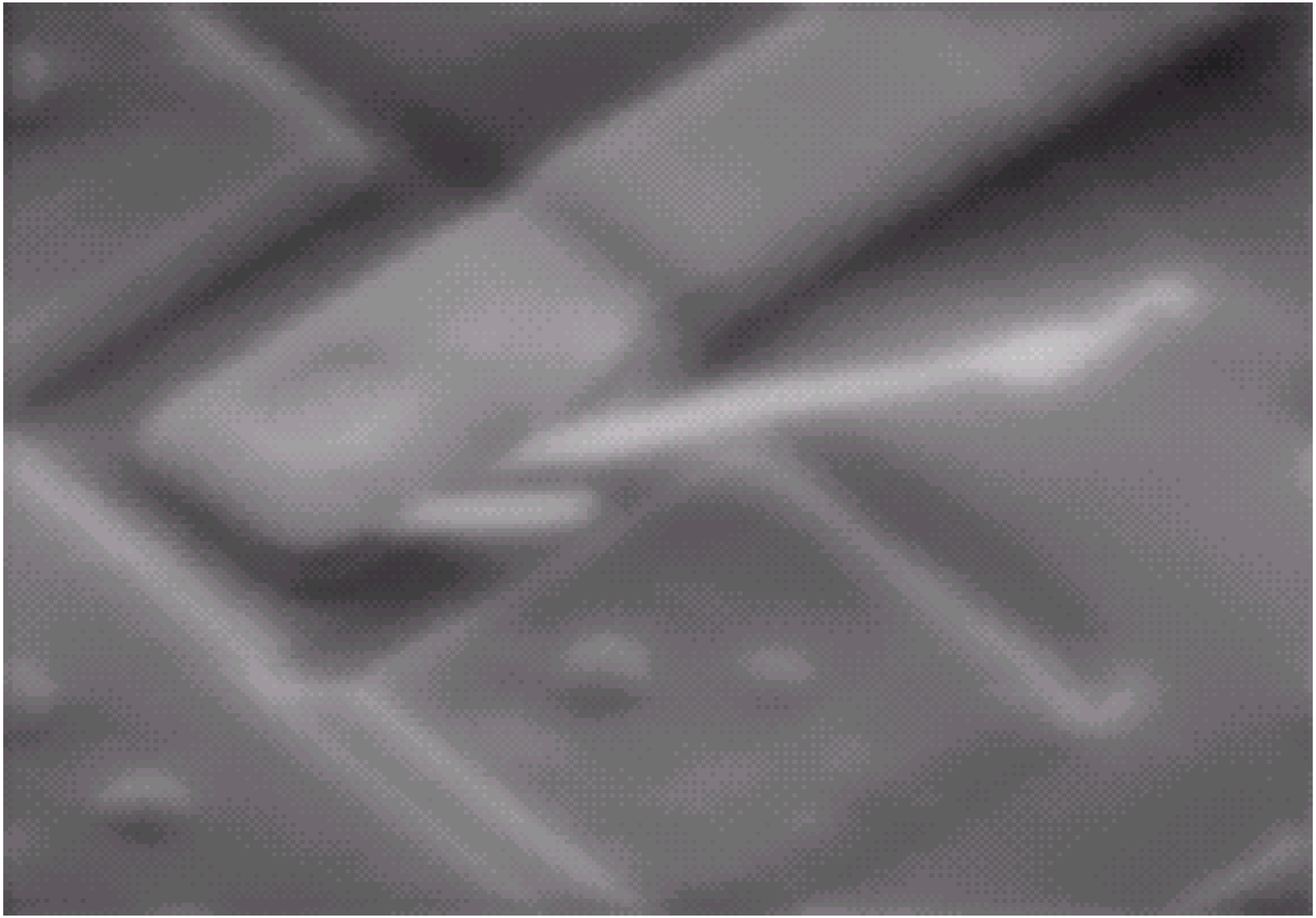
Low Pass Filter



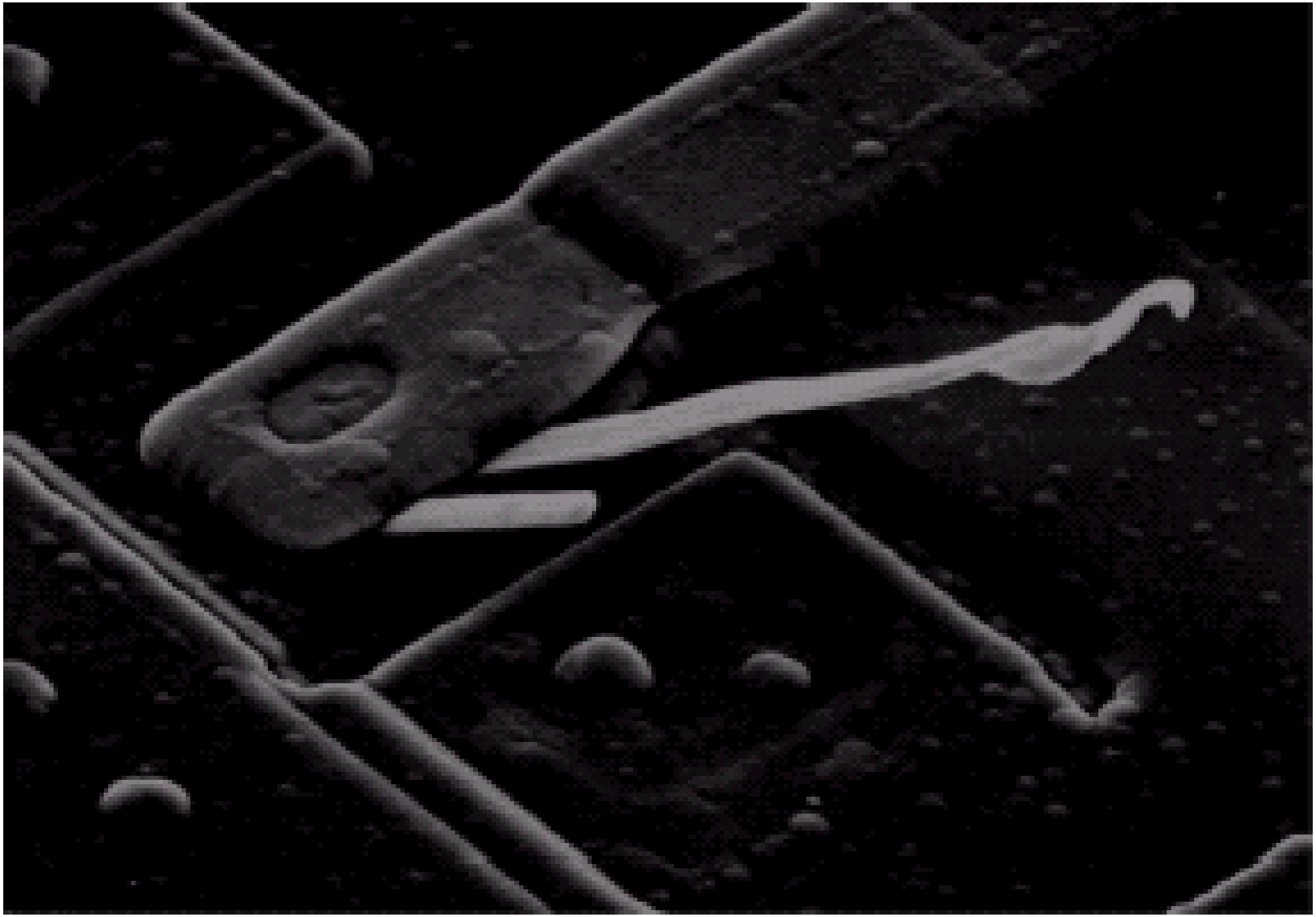


High Pass Filter

Some Basic Frequency Domain Filters



Some Basic Frequency Domain Filters



Smoothing Frequency Domain Filters

Smoothing is achieved in the frequency domain by dropping out the high frequency components

The basic model for filtering is:

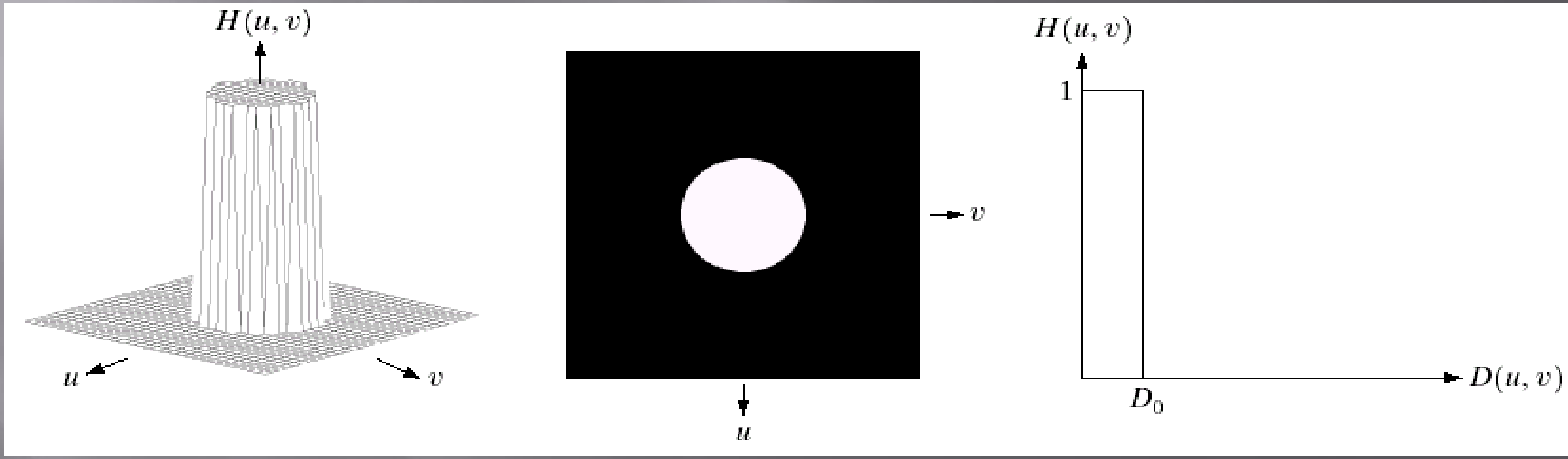
$$G(u,v) = H(u,v)F(u,v)$$

where $F(u,v)$ is the Fourier transform of the image being filtered and $H(u,v)$ is the filter transform function

Low pass filters – only pass the low frequencies, drop the high ones

Ideal Low Pass Filter

Simply cut off all high frequency components that are a specified distance D_0 from the origin of the transform



Ideal Low Pass Filter (cont…)

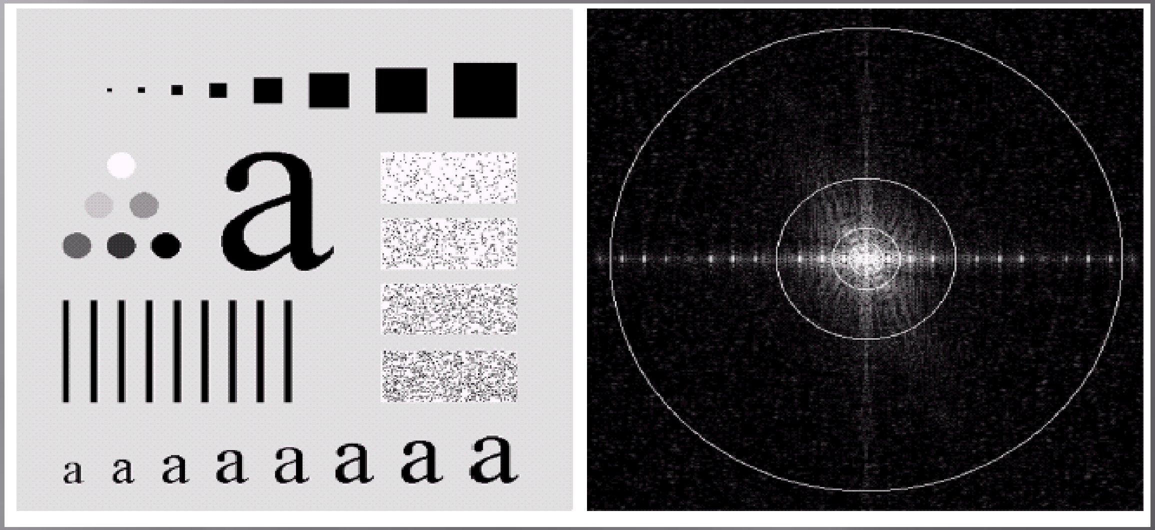
The transfer function for the ideal low pass filter can be given as:

$$H(u,v) = \begin{cases} 1 \text{ if } D(u,v) \le D_0 \\ 0 \text{ if } D(u,v) > D_0 \end{cases}$$

where $D(u,v)$ is given as:

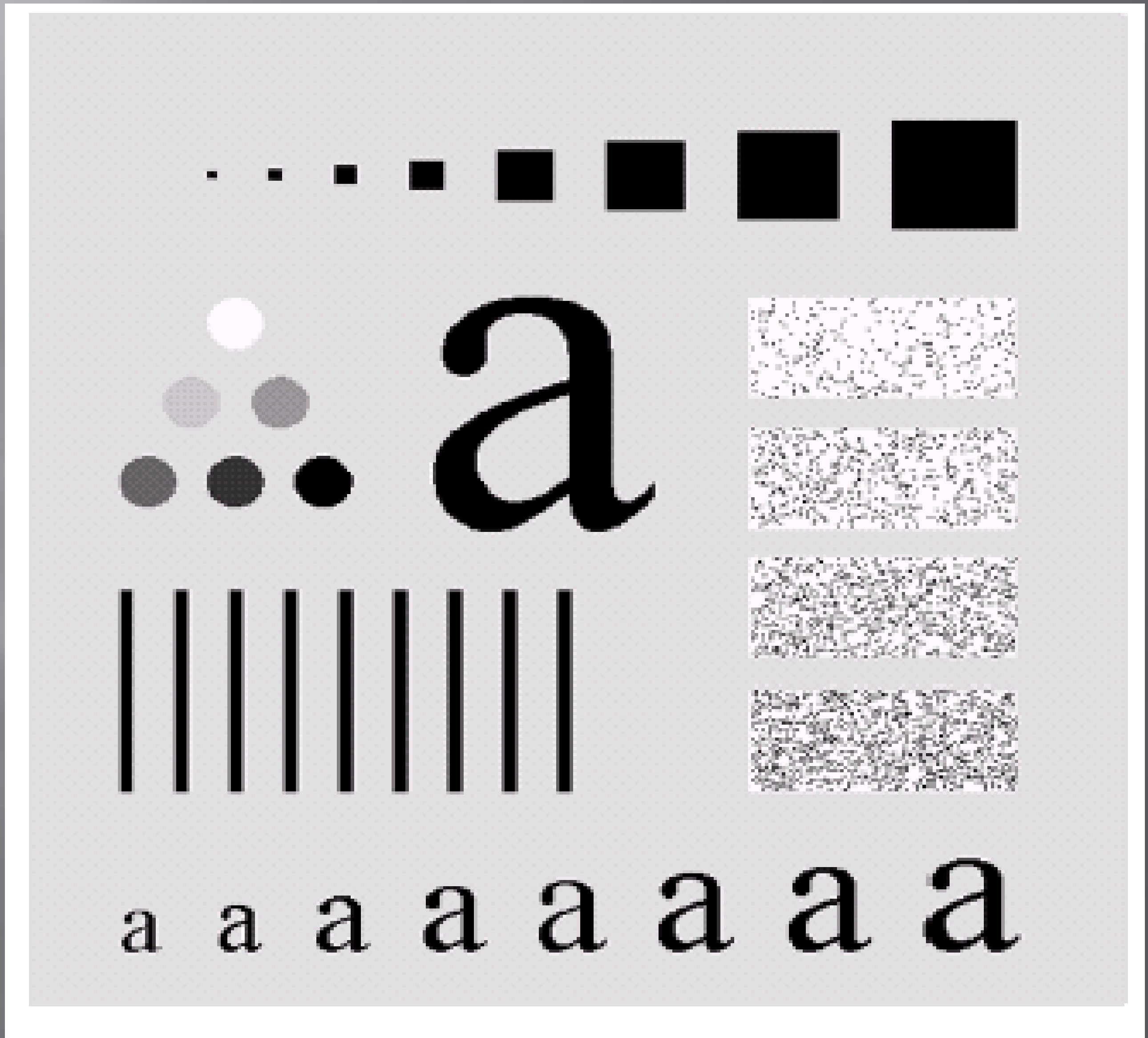
$$D(u,v) = [(u - M/2)^2 + (v - N/2)^2]^{1/2}$$

Ideal Low Pass Filter (cont…)

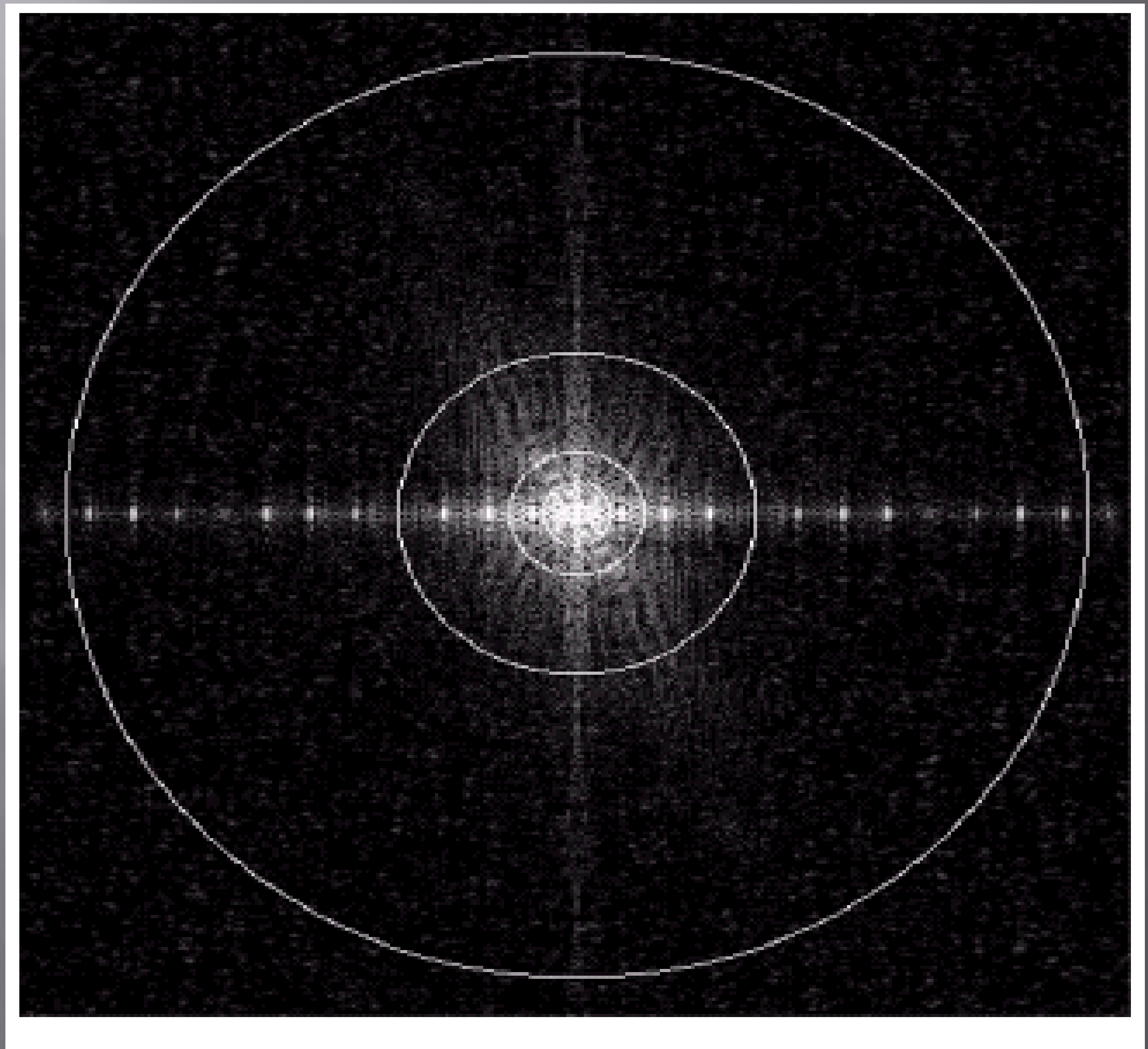


Above we show an image, it's Fourier spectrum and a series of ideal low pass filters of radius 5, 15, 30, 80 and 230 superimposed on top of it

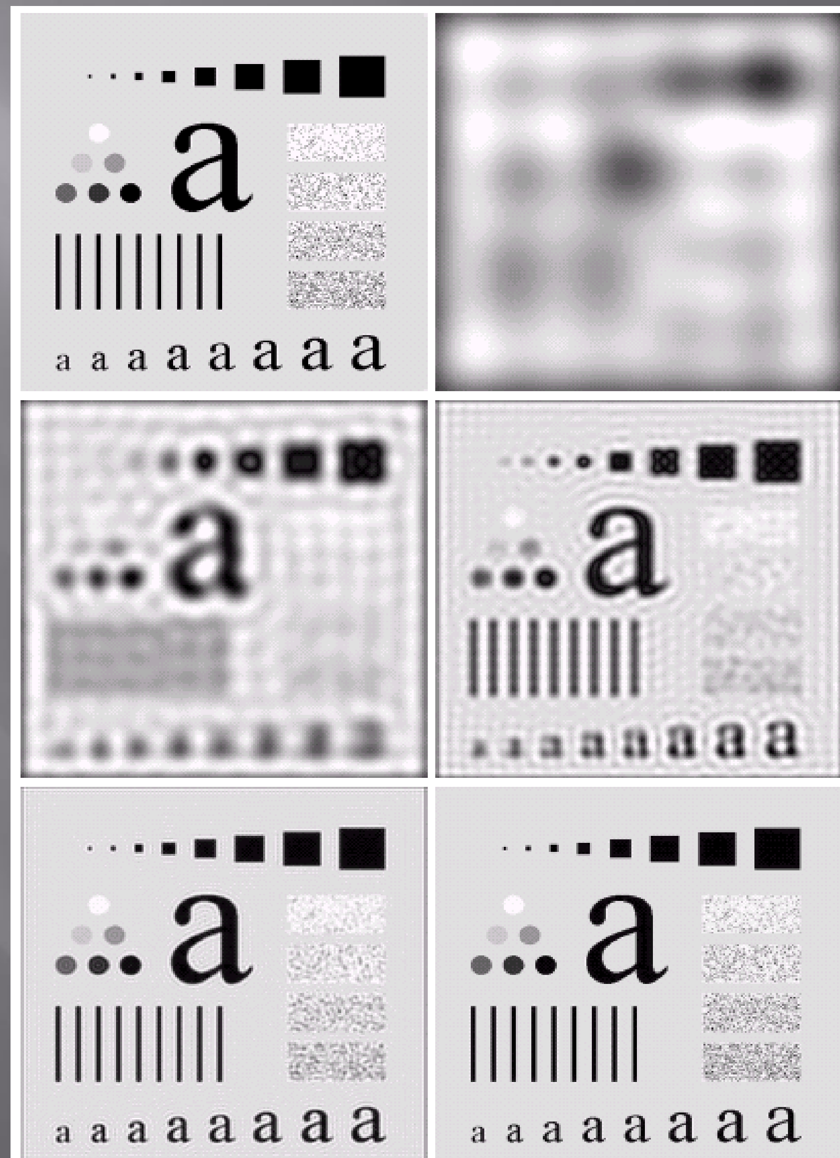
Ideal Low Pass Filter (cont…)



Ideal Low Pass Filter (cont…)



Ideal Low Pass Filter (cont…)



Original image

Result of filtering with ideal low pass filter of radius 5

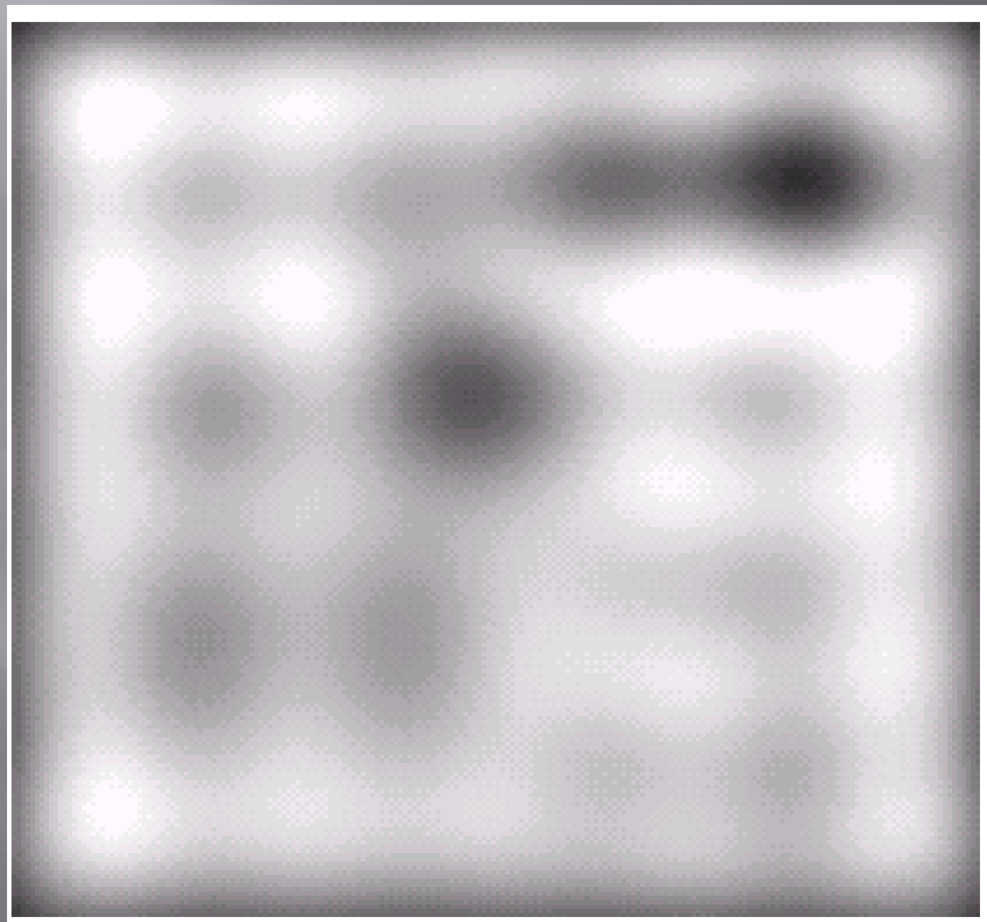
Result of filtering with ideal low pass filter of radius 15

Result of filtering with ideal low pass filter of radius 30

Result of filtering with ideal low pass filter of radius 80

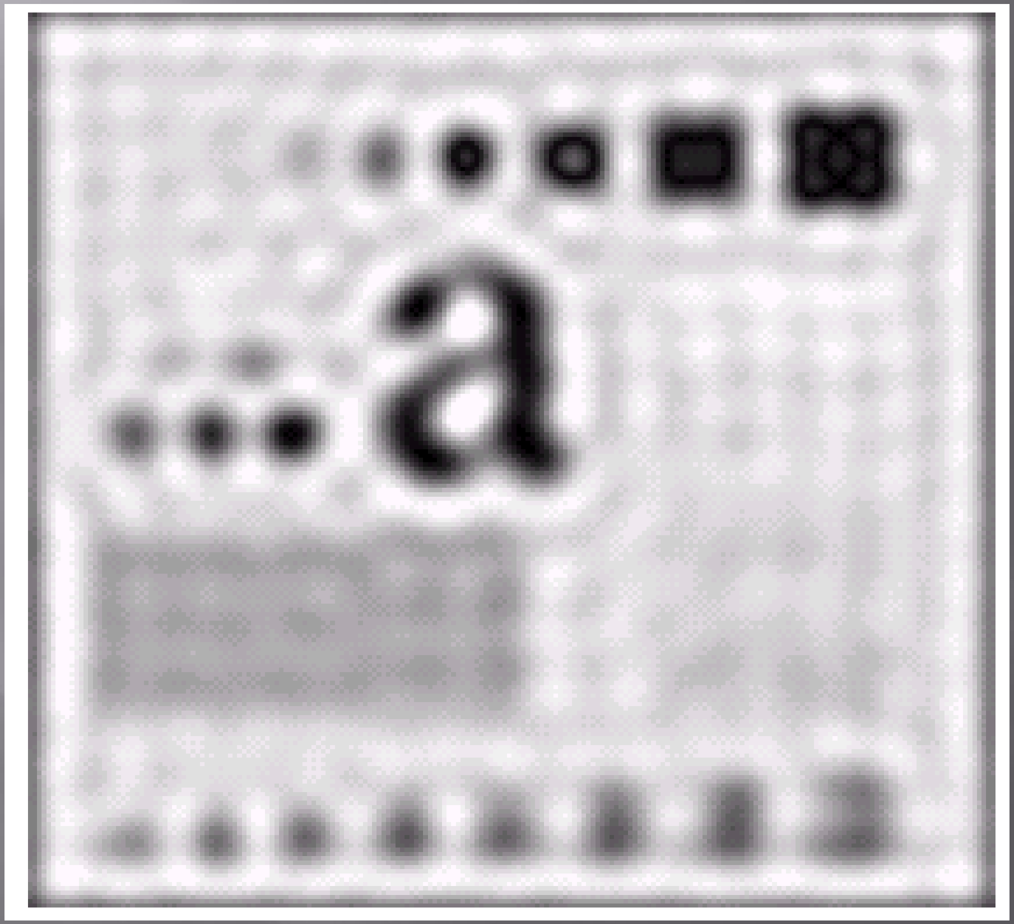
Result of filtering with ideal low pass filter of radius 230

Ideal Low Pass Filter (cont…)



Result of filtering with ideal low pass filter of radius 5

Ideal Low Pass Filter (cont…)

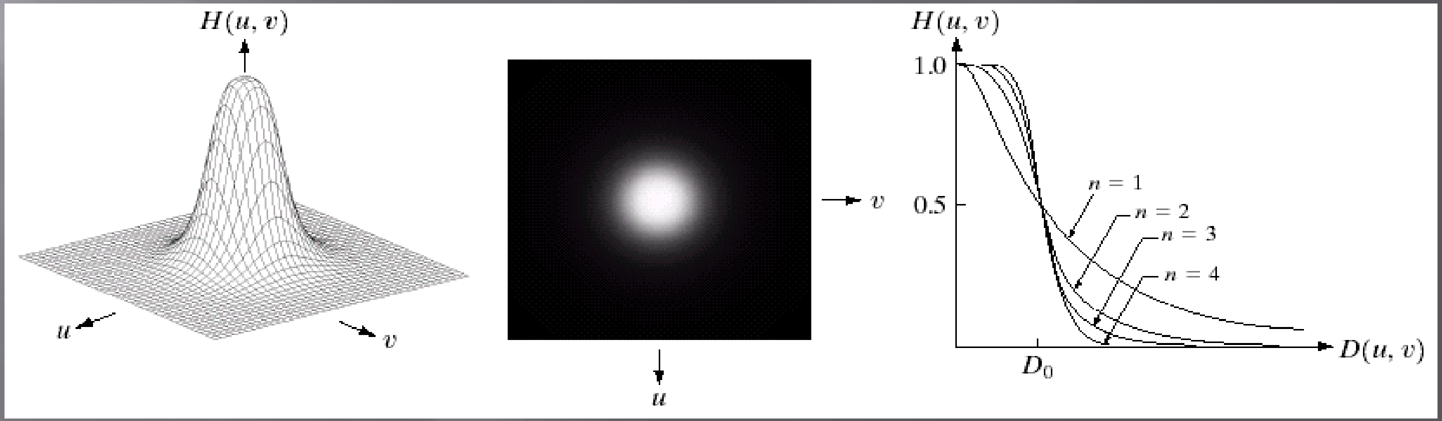


Result of filtering with ideal low pass filter of radius 15

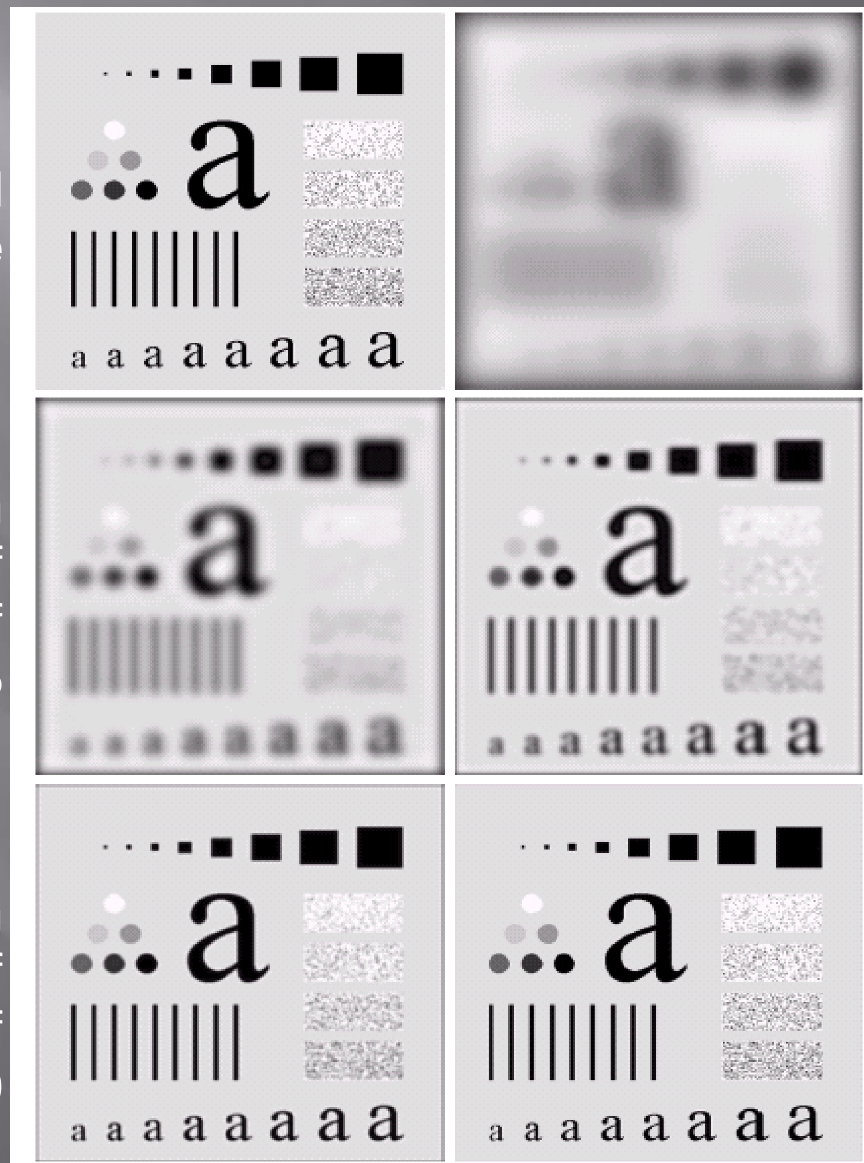
Butterworth Lowpass Filters

The transfer function of a Butterworth lowpass filter of order n with cutoff frequency at distance D_0 from the origin is defined as:

$$H(u,v) = \frac{1}{1 + [D(u,v)/D_0]^{2n}}$$



Butterworth Lowpass Filter (cont…)



Original image

Result of filtering with Butterworth filter of order 2 and cutoff radius 5

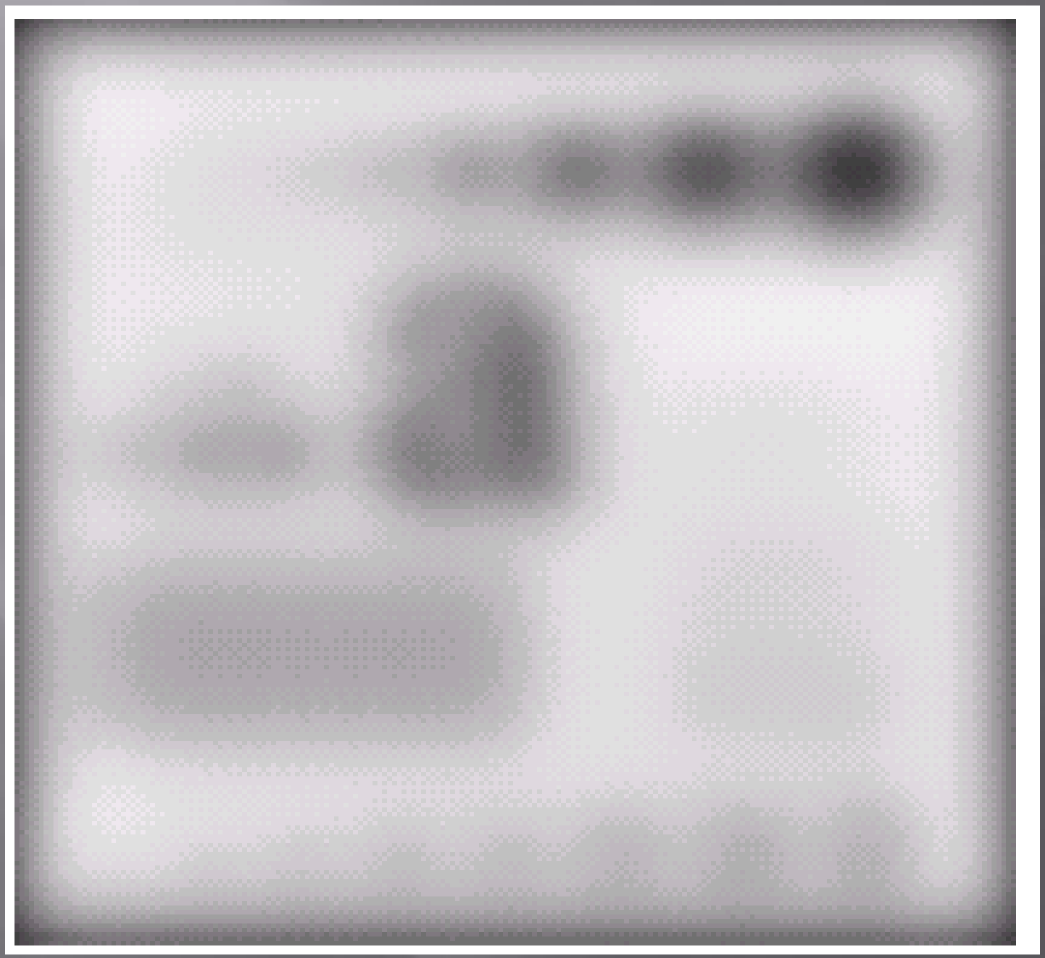
Result of filtering with Butterworth filter of order 2 and cutoff radius 15

Result of filtering with Butterworth filter of order 2 and cutoff radius 30

Result of filtering with Butterworth filter of order 2 and cutoff radius 80

Result of filtering with Butterworth filter of order 2 and cutoff radius 230

Butterworth Lowpass Filter (cont…)



Result of filtering with Butterworth filter of order 2 and cutoff radius 5

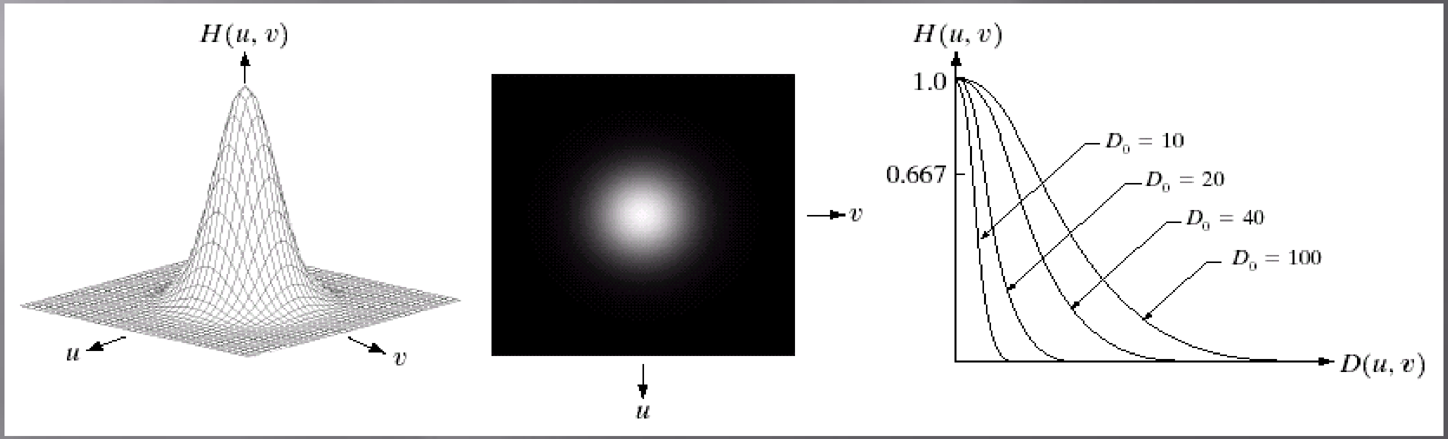
Butterworth Lowpass Filter (cont…)

Result of filtering with Butterworth filter of order 2 and cutoff radius 15

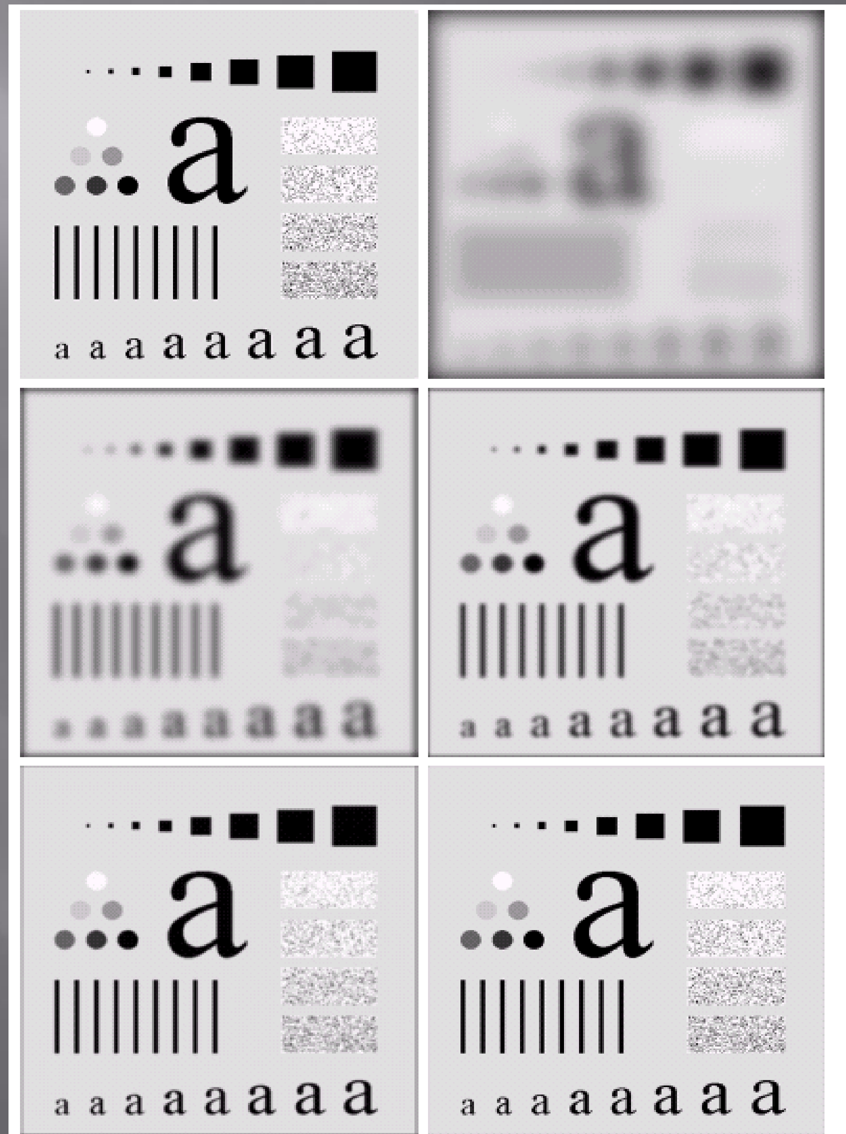
Gaussian Lowpass Filters

The transfer function of a Gaussian lowpass filter is defined as:

$$H(u,v) = e^{-D^2(u,v)/2D_0^2}$$



Gaussian Lowpass Filters (cont…)



Original image

Result of filtering with Gaussian filter with cutoff radius 5

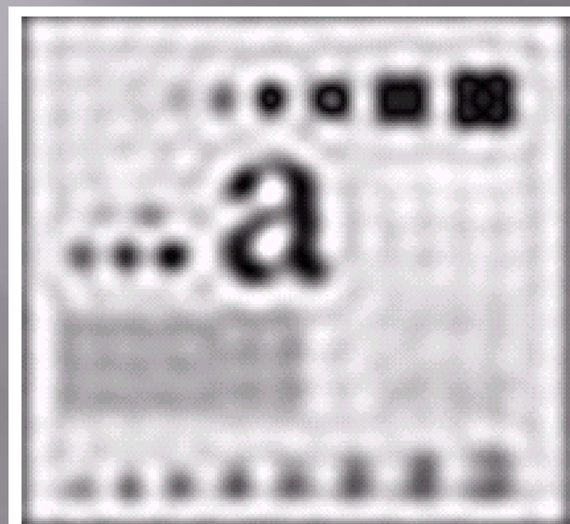
Result of filtering with Gaussian filter with cutoff radius 15

Result of filtering with Gaussian filter with cutoff radius 30

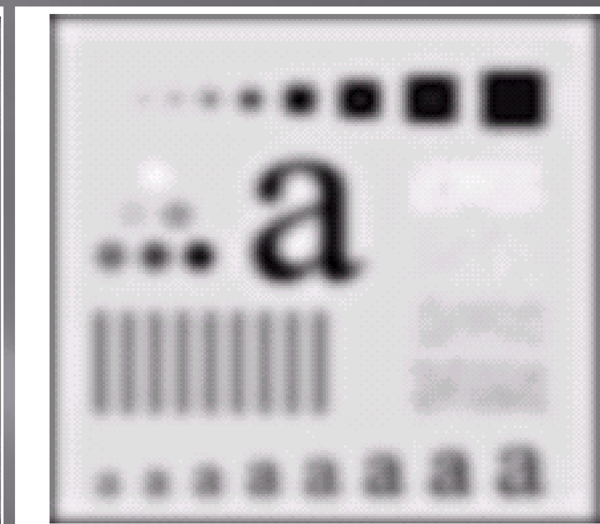
Result of filtering with Gaussian filter with cutoff radius 85

Result of filtering with Gaussian filter with cutoff radius 230

Lowpass Filters Compared



Result of filtering with ideal low pass filter of radius 15

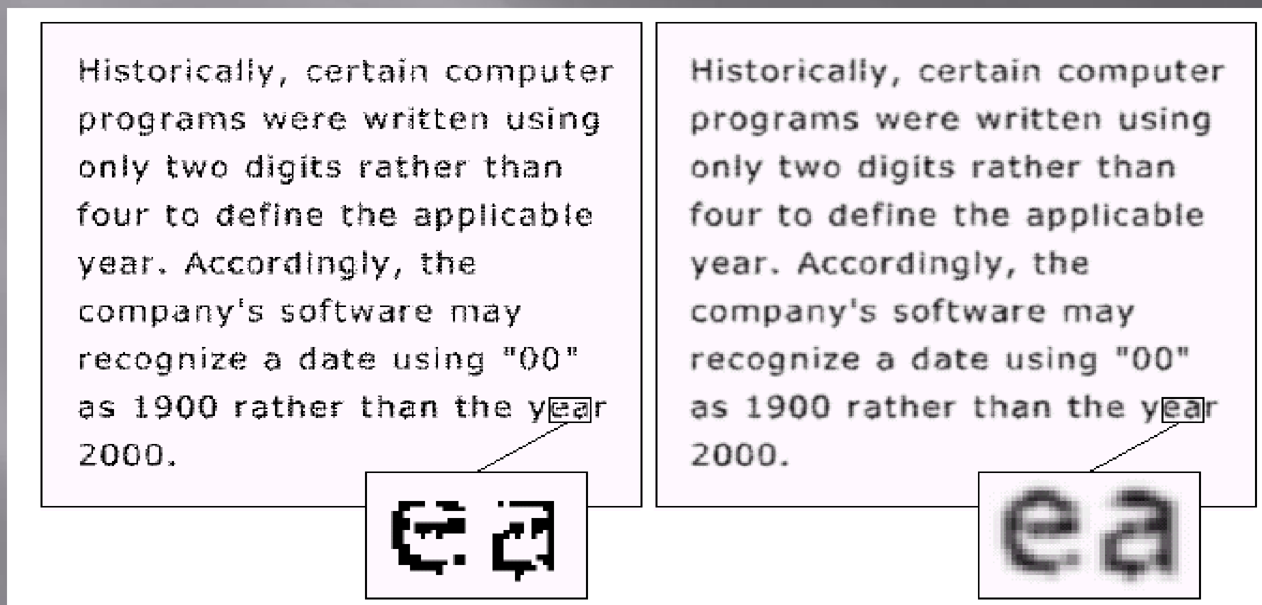


Result of filtering with Butterworth filter of order 2 and cutoff radius 15

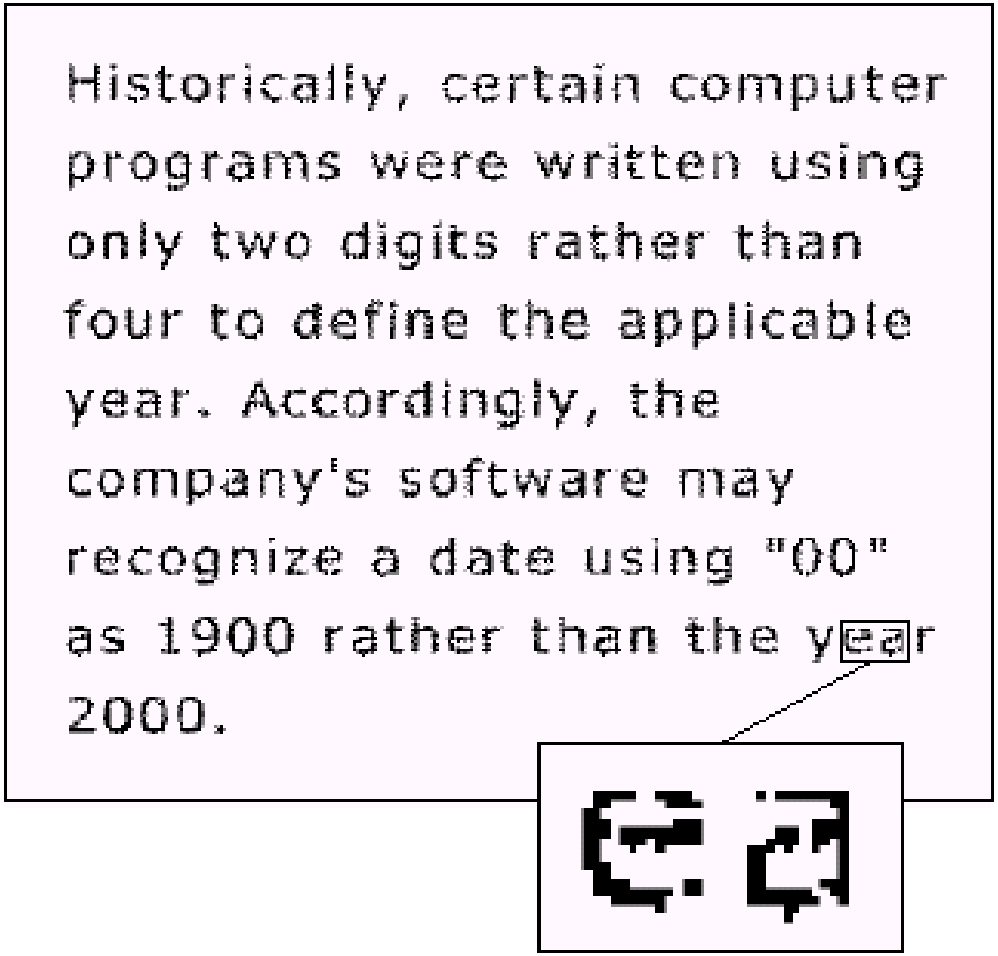
Result of filtering with Gaussian filter with cutoff radius 15

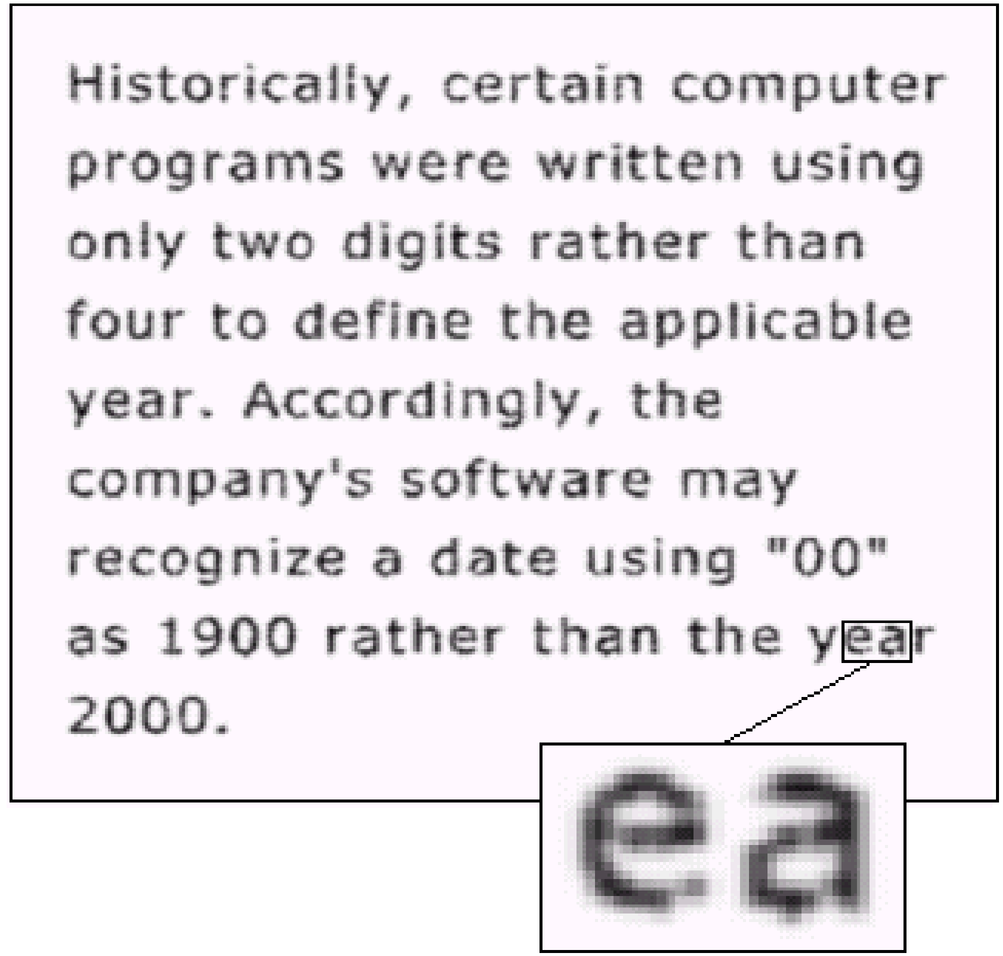
Lowpass Filtering Examples

A low pass Gaussian filter is used to connect broken text



Lowpass Filtering Examples





Lowpass Filtering Examples (cont…)

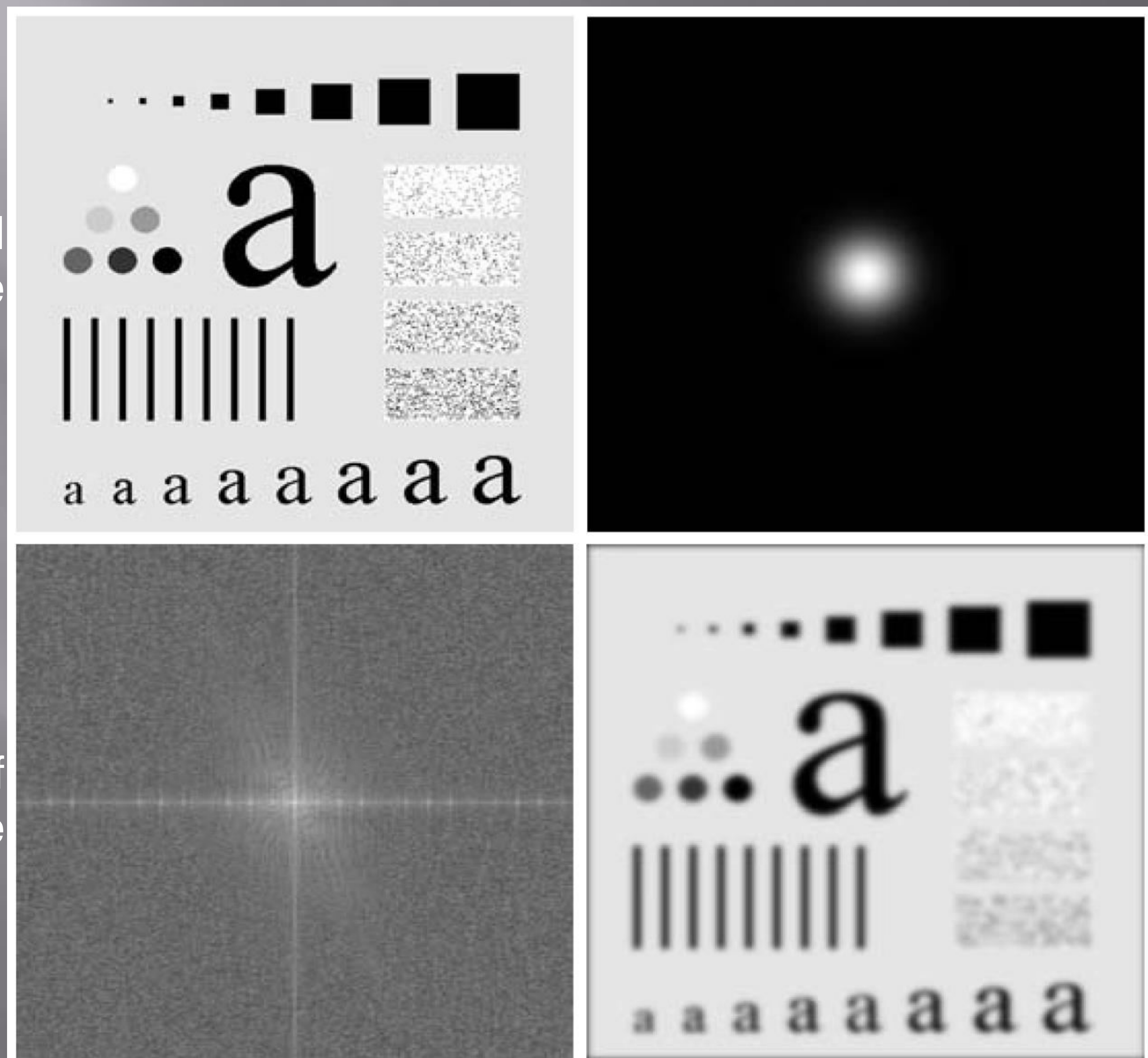
Different lowpass Gaussian filters used to remove blemishes in a photograph

Lowpass Filtering Examples (cont…)

Lowpass Filtering Examples (cont…)

Original image

Gaussian lowpass filter



Spectrum of original image

Processed image

Sharpening in the Frequency Domain

- Edges and fine detail in images are associated with high frequency components
- *High pass filters* – only pass the high frequencies, drop the low ones
- High pass frequencies are precisely the reverse of low pass filters, so:

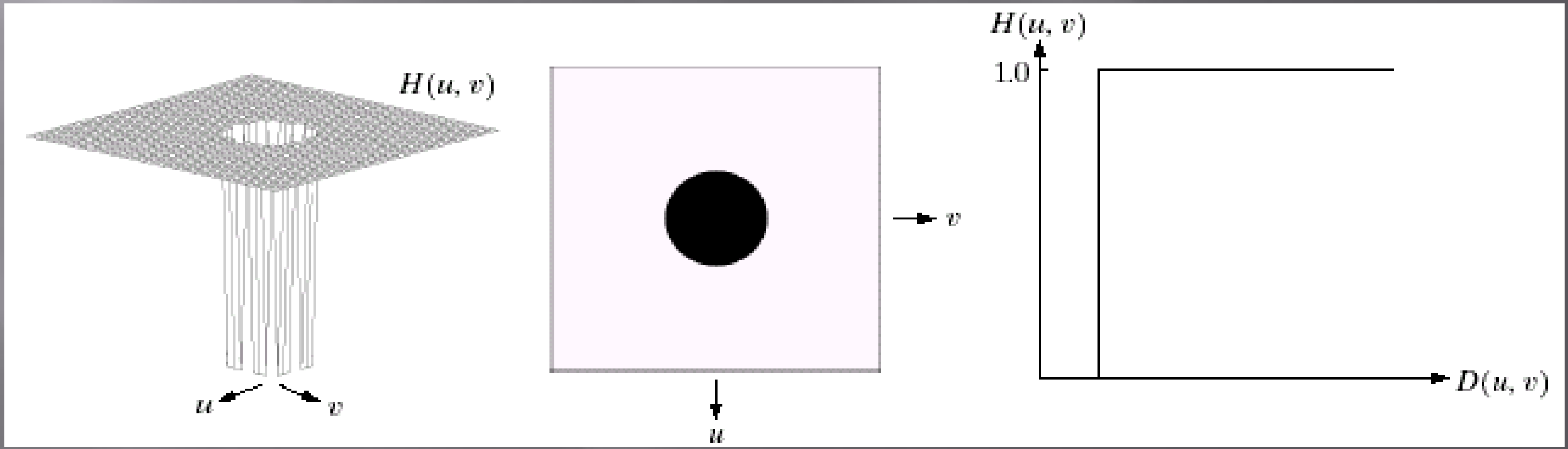
$$H_{hp}(u, v) = 1 - H_{lp}(u, v)$$

Ideal High Pass Filters

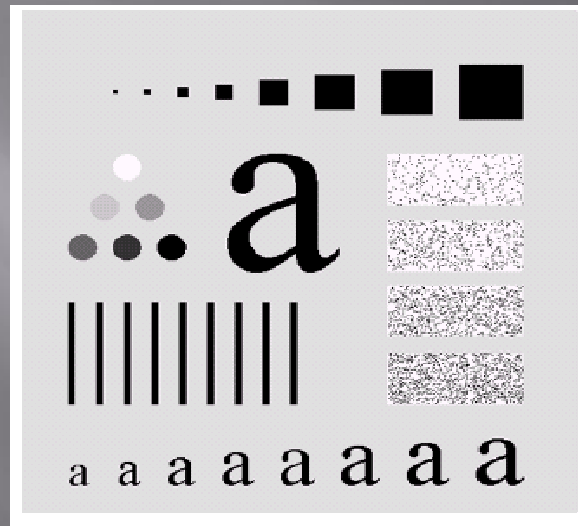
The ideal high pass filter is given as:

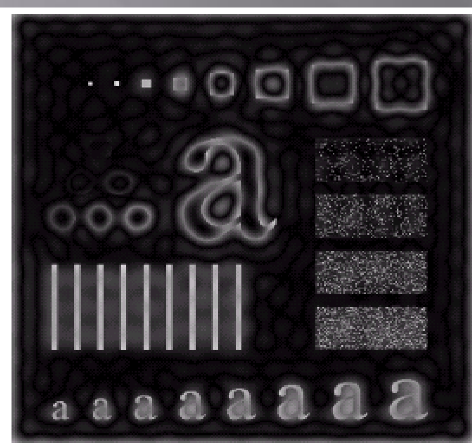
$$H(u,v) = \begin{cases} 0 \text{ if } D(u,v) \le D_0 \\ 1 \text{ if } D(u,v) > D_0 \end{cases}$$

where D_0 is the cut off distance as before

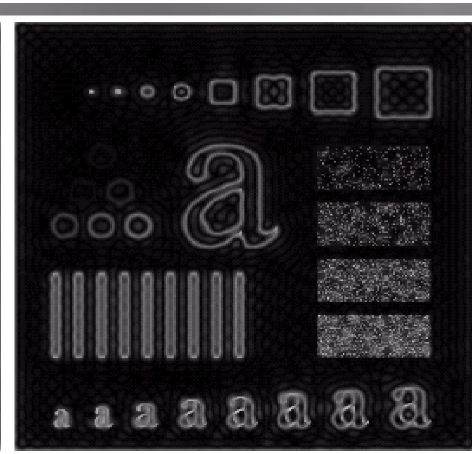


Ideal High Pass Filters (cont…)

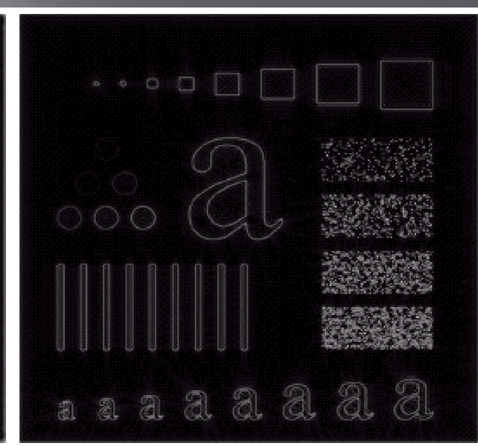




Results of ideal high pass filtering with $D_0 = 15$



Results of ideal high pass filtering with $D_0 = 30$



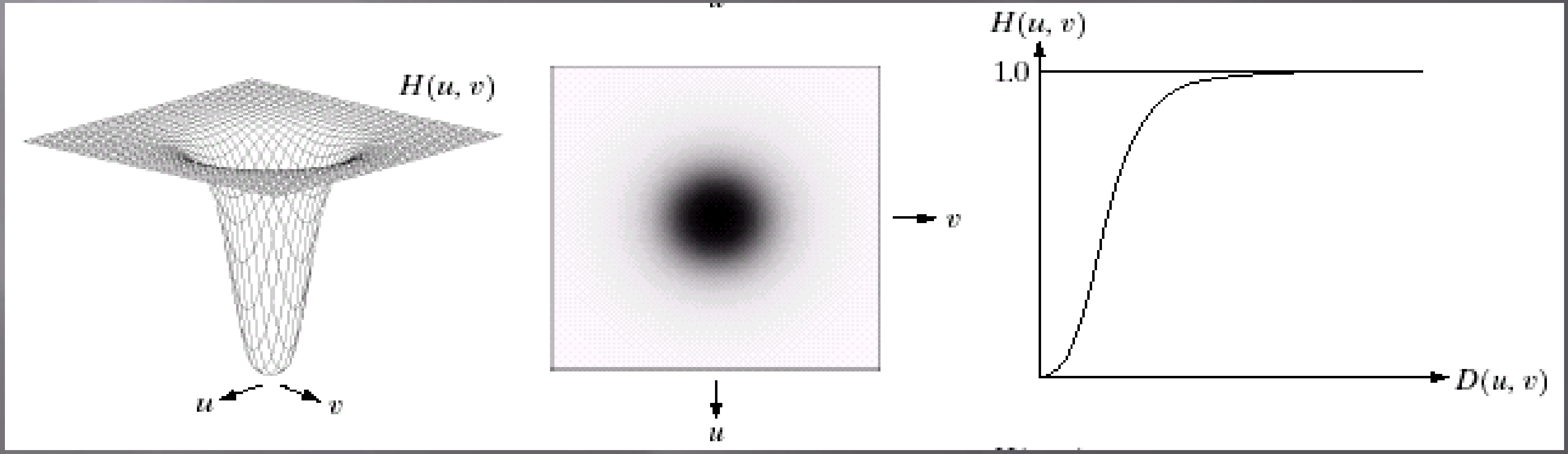
Results of ideal high pass filtering with $D_0 = 80$

Butterworth High Pass Filters

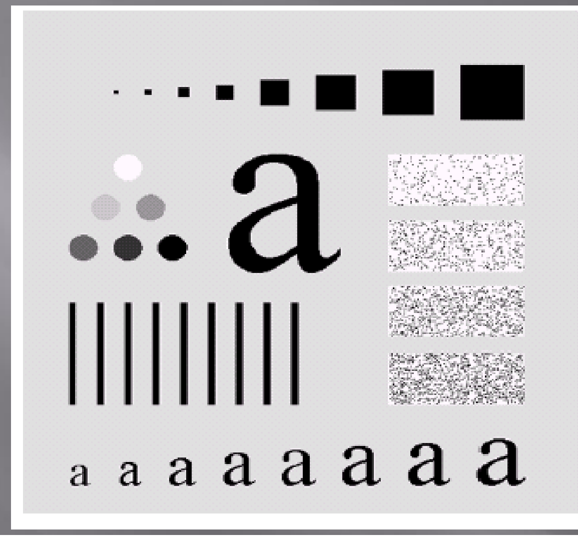
The Butterworth high pass filter is given as:

$$H(u,v) = \frac{1}{1 + [D_0 / D(u,v)]^{2n}}$$

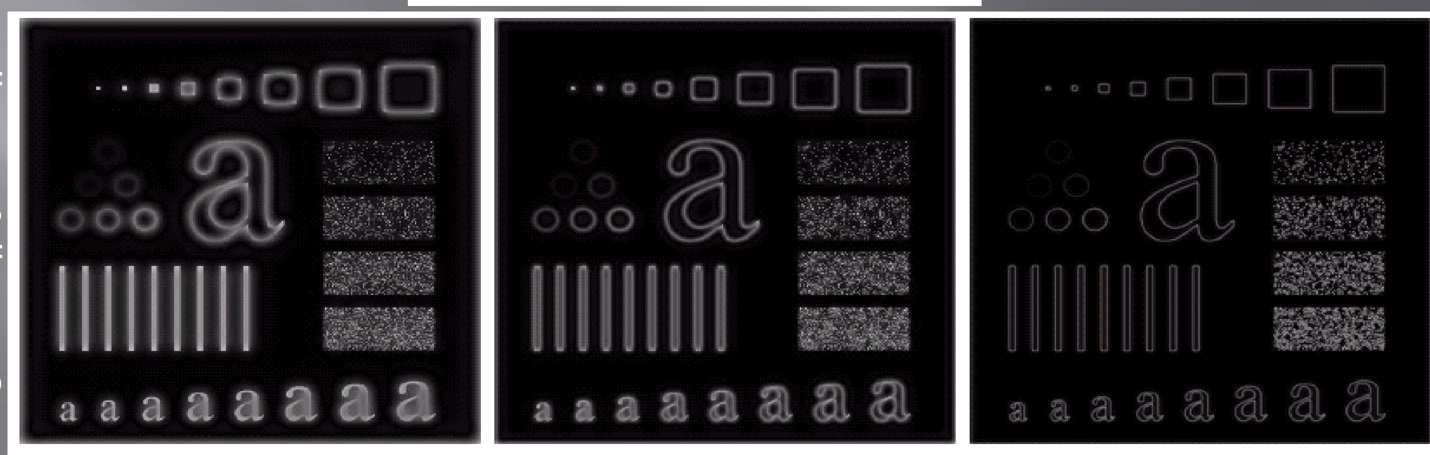
where n is the order and D_0 is the cut off distance as before



Butterworth High Pass Filters (cont…)



Results of Butterworth high pass filtering of order 2 with D_0 = 15



Results of Butterworth high pass filtering of order 2 with D_0 = 80

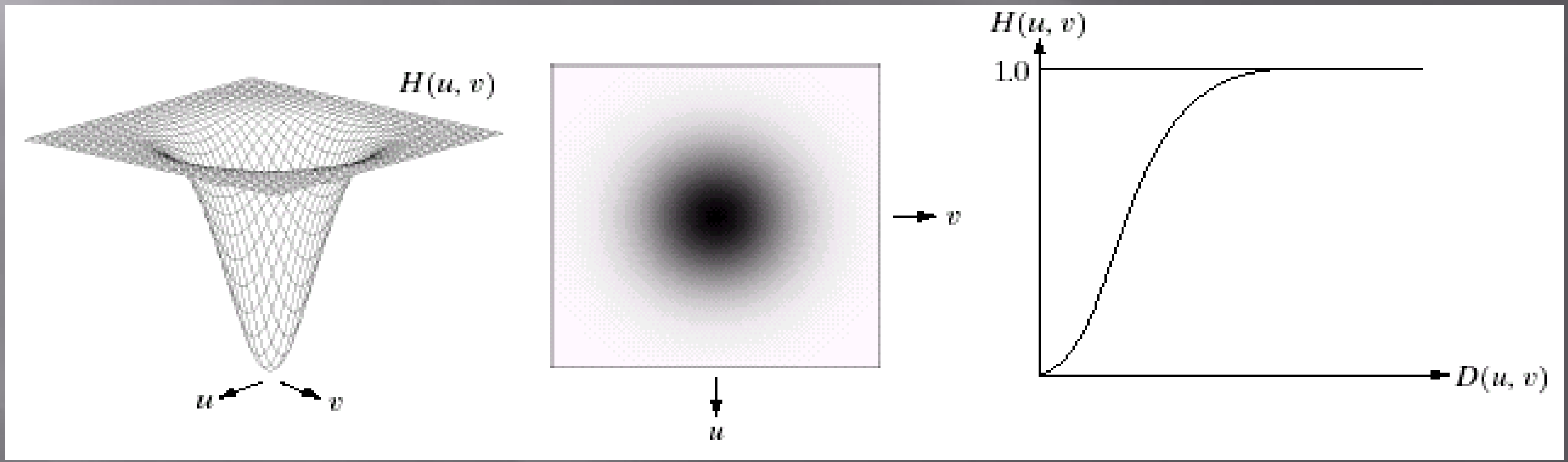
Results of Butterworth high pass filtering of order 2 with D_0 = 30

Gaussian High Pass Filters

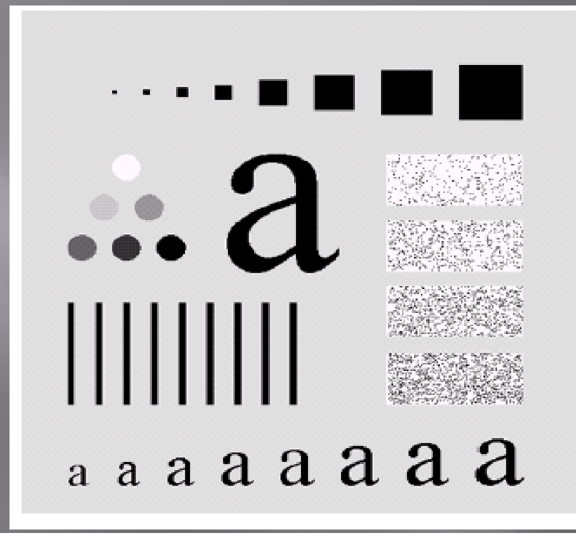
The Gaussian high pass filter is given as:

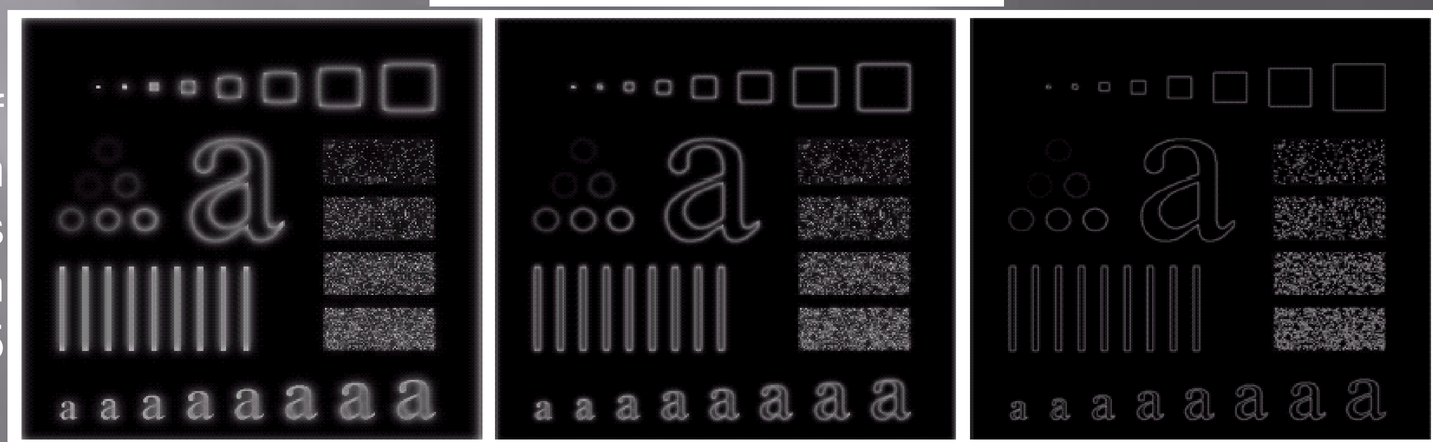
$$H(u,v) = 1 - e^{-D^2(u,v)/2D_0^{\,2}}$$

where D_0 is the cut off distance as before



Gaussian High Pass Filters (cont…)



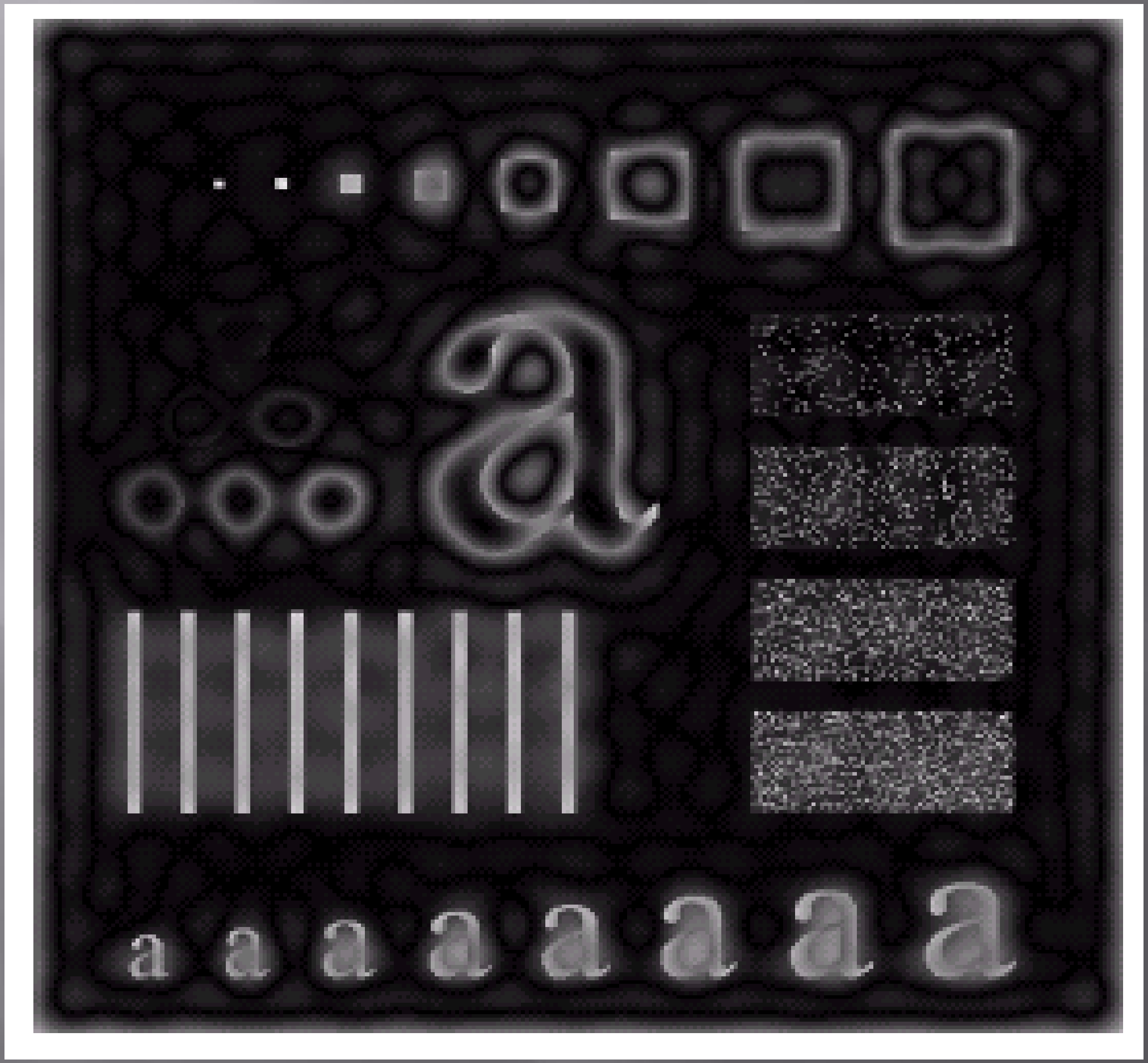


Results of Gaussian high pass filtering with $D_0 = 15$

Results of Gaussian high pass filtering with $D_0 = 30$

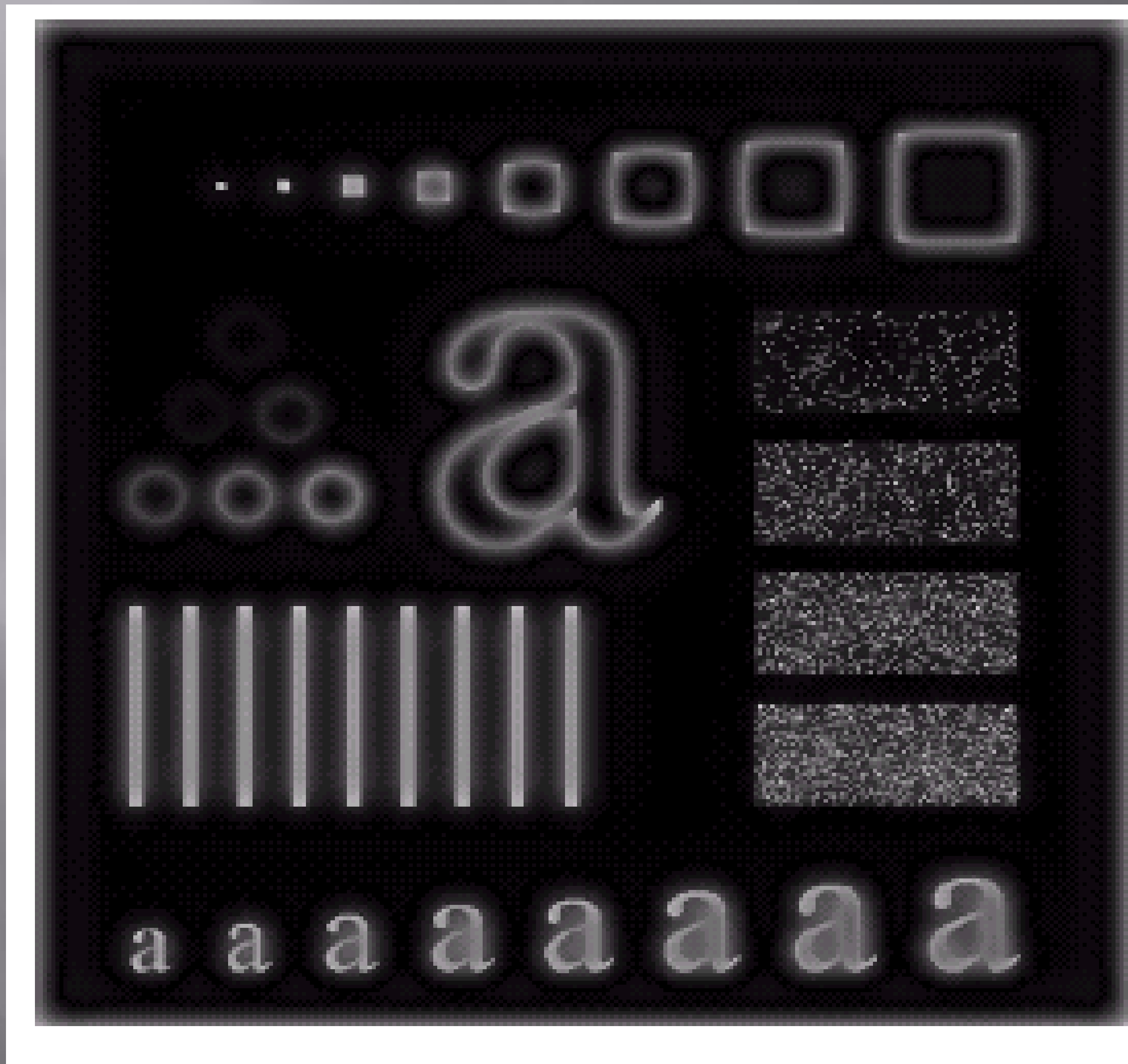
Results of Gaussian high pass filtering with $D_0 = 80$

Highpass Filter Comparison



Results of ideal high pass filtering with $D_0 = 15$

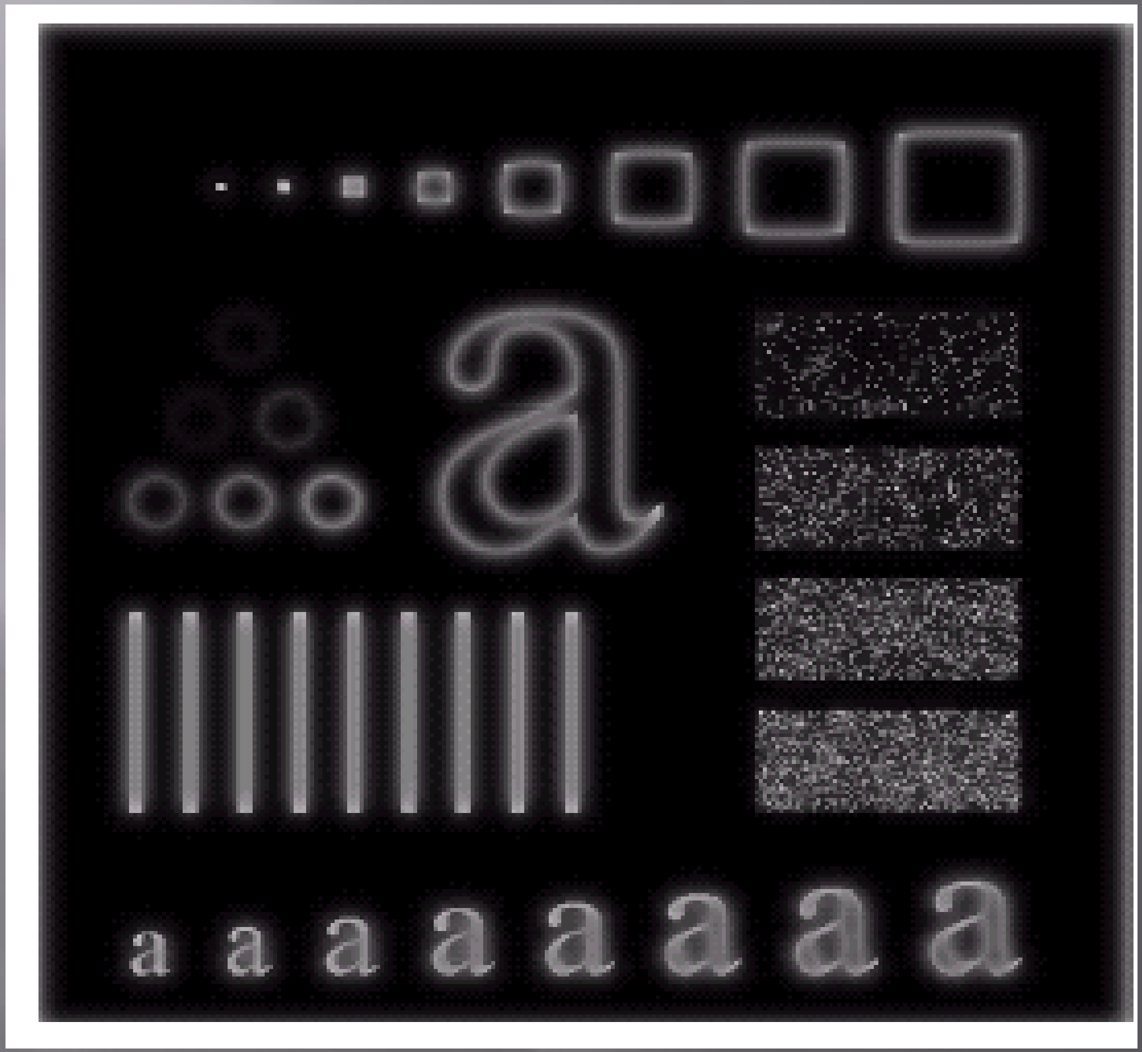
Highpass Filter Comparison



Results of Butterworth high pass filtering of order 2 with $D_0 = 15$

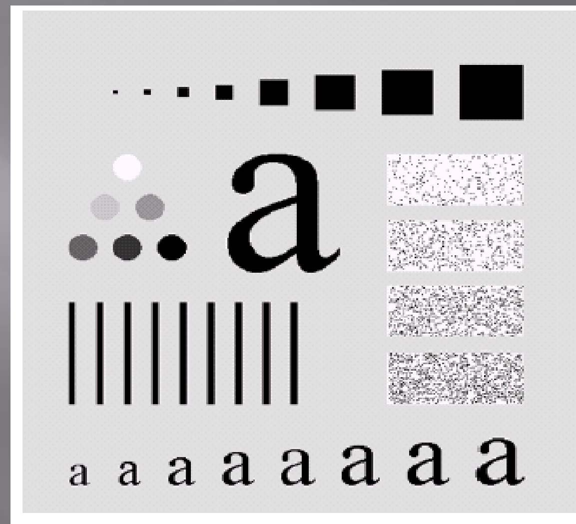
Images taken from Gonzalez & Woods, Digital Image Processing (2002)

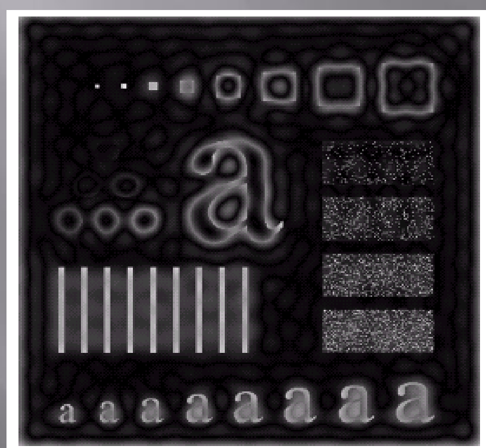
Highpass Filter Comparison



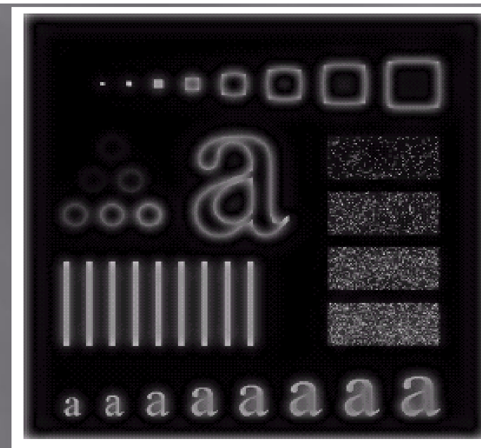
Results of Gaussian high pass filtering with $D_0 = 15$

Highpass Filter Comparison

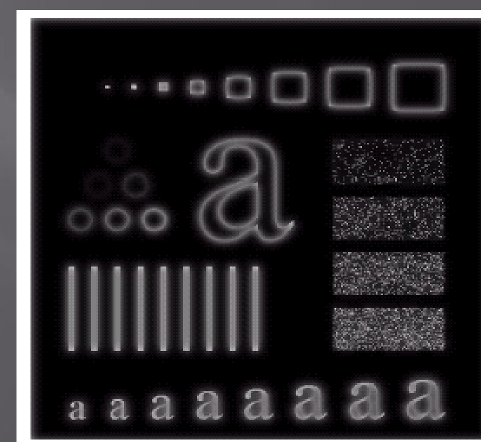




Results of ideal high pass filtering with $D_0 = 15$

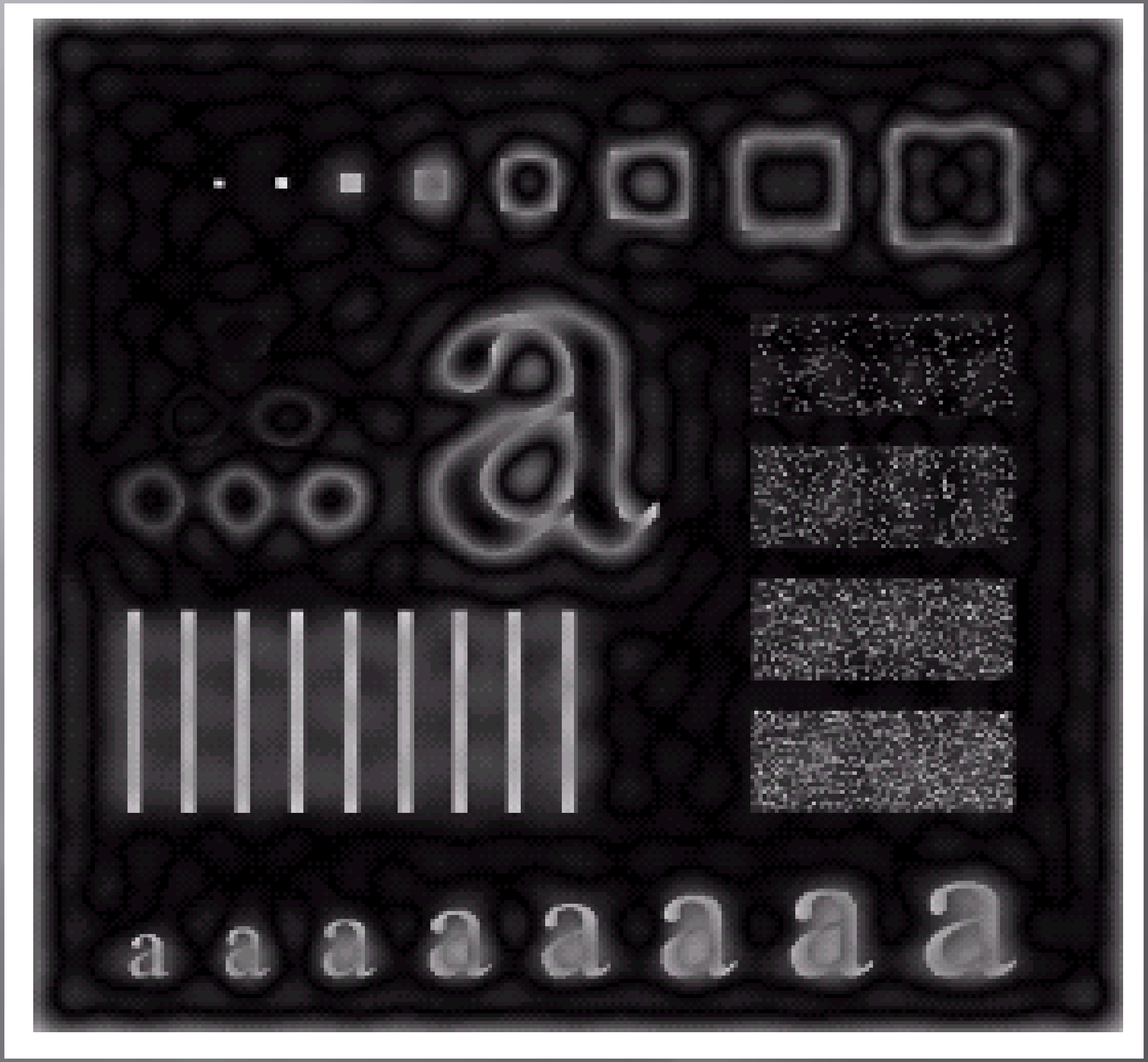


Results of Butterworth high pass filtering of order 2 with $D_0 = 15$



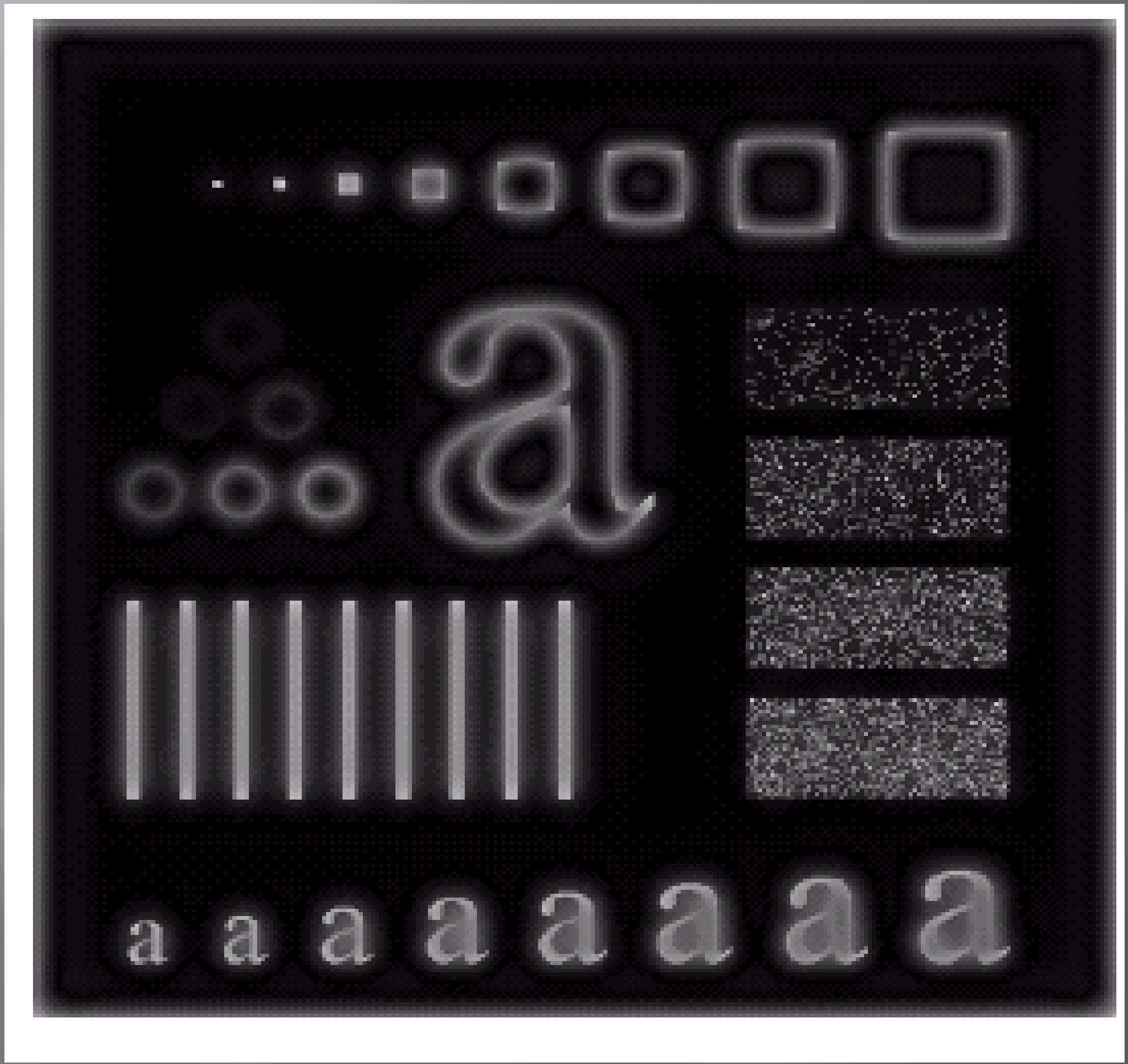
Results of Gaussian high pass filtering with $D_0 = 15$

Highpass Filter Comparison



Results of ideal high pass filtering with $D_0 = 15$

Highpass Filter Comparison



Results of Butterworth high pass filtering of order 2 with D_0 = 15

Homomorphic Filtering

- If the image model is based on illumination-reflectance, then frequency domain procedures are not as easy to perform.
- The main reason is that illumination and reflectance components of the model are not separable.
- To be able to improve appearance of an image by simultaneous brightness range compression and contrast enhancement it is necessary to separate the two components.
- As you recall, an image can be modeled mathematically in terms of illumination and reflectance as follow: $f(x,y) = I(x,y)\ r(x,y)$