

Digital Image Processing

Image Enhancement:
Filtering in the Frequency Domain

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

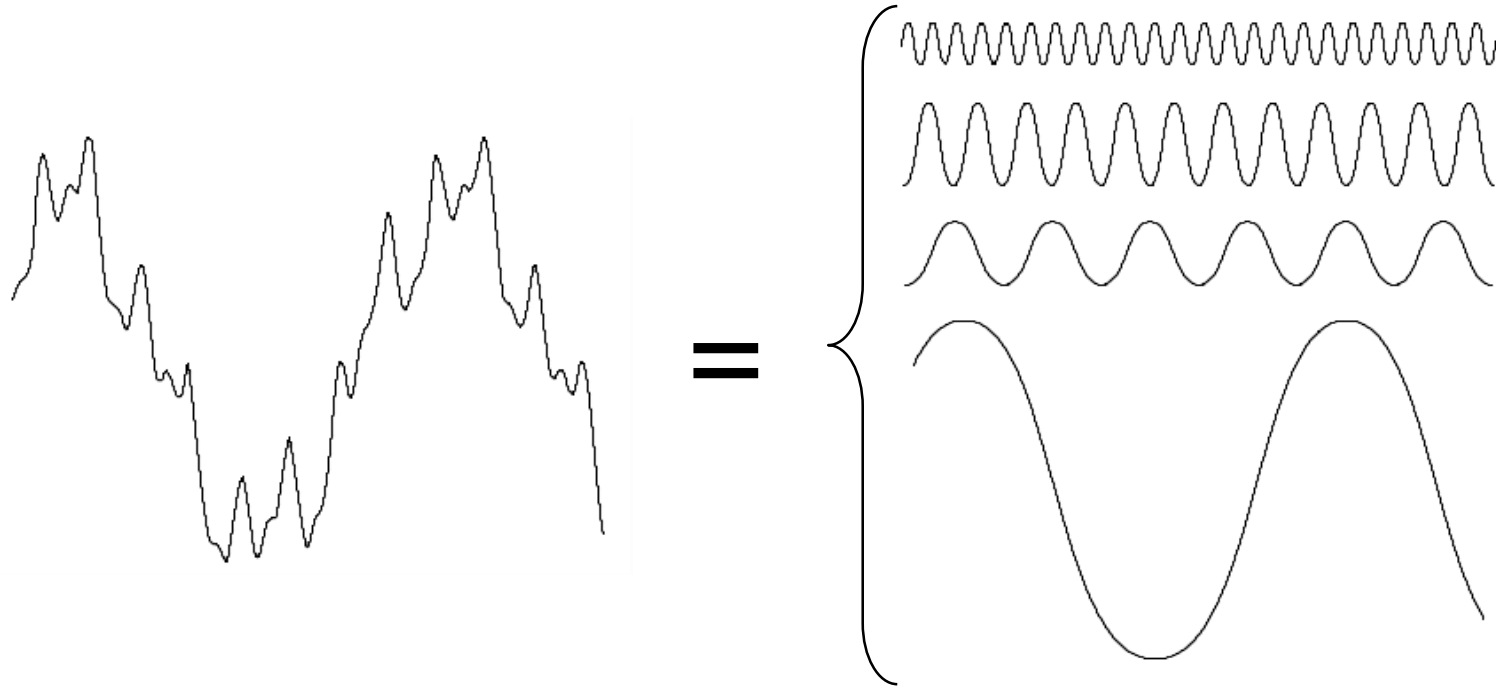


Fourier was born in Auxerre,
France in 1768

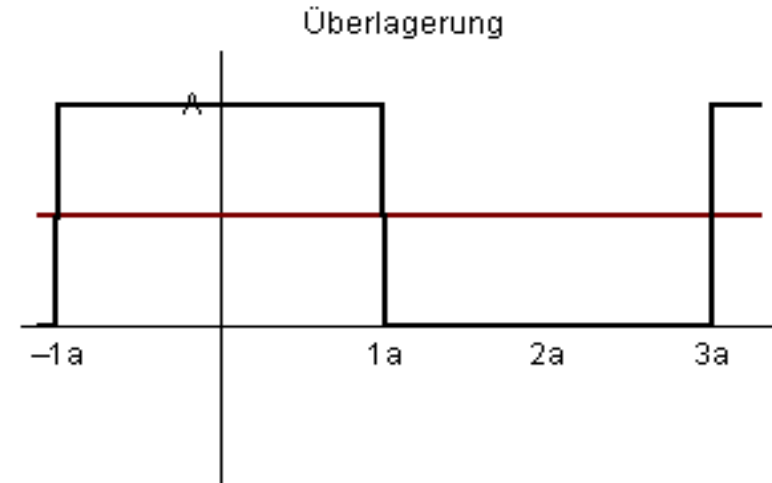
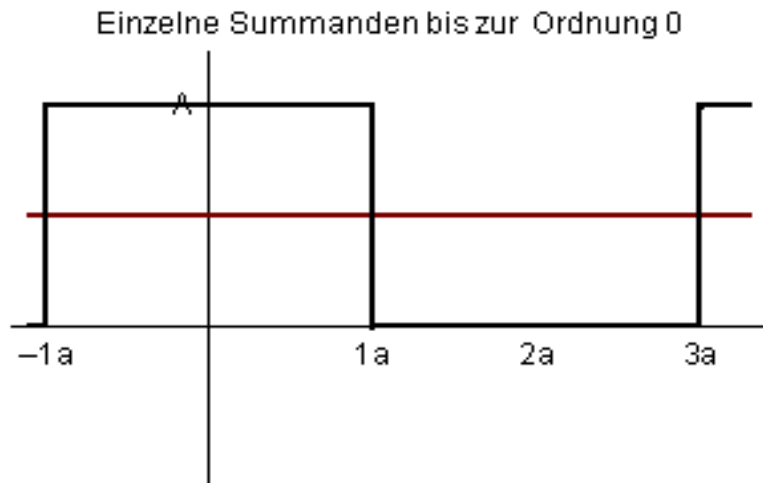
- Most famous for his work “*La Théorie Analytique de la Chaleur*” published in 1822
- Translated into English in 1878: “*The Analytic Theory of Heat*”

Nobody paid much attention when the work was first published

One of the most important mathematical theories in modern engineering



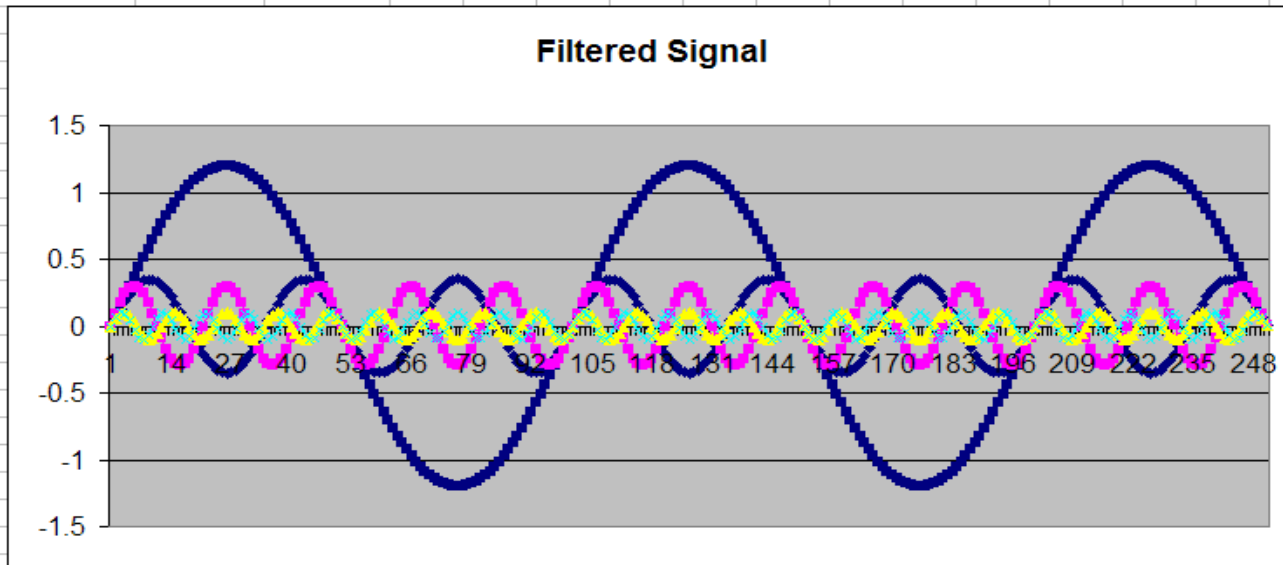
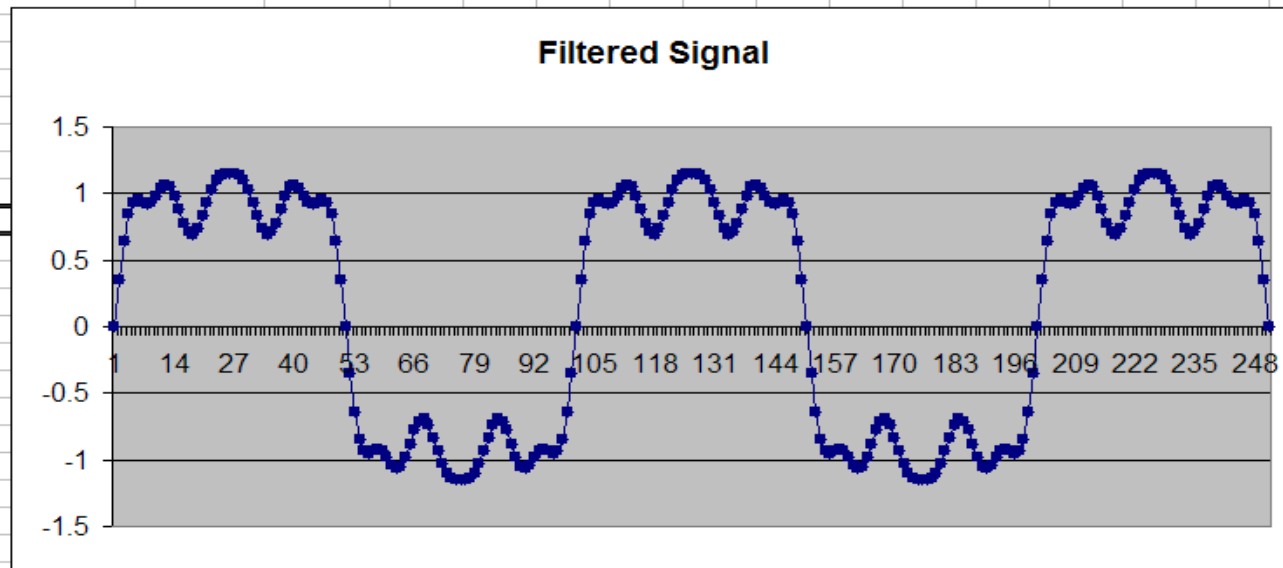
Any function that periodically repeats itself can be expressed as a sum of sines and cosines of different frequencies each multiplied by a different coefficient – a *Fourier series*



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



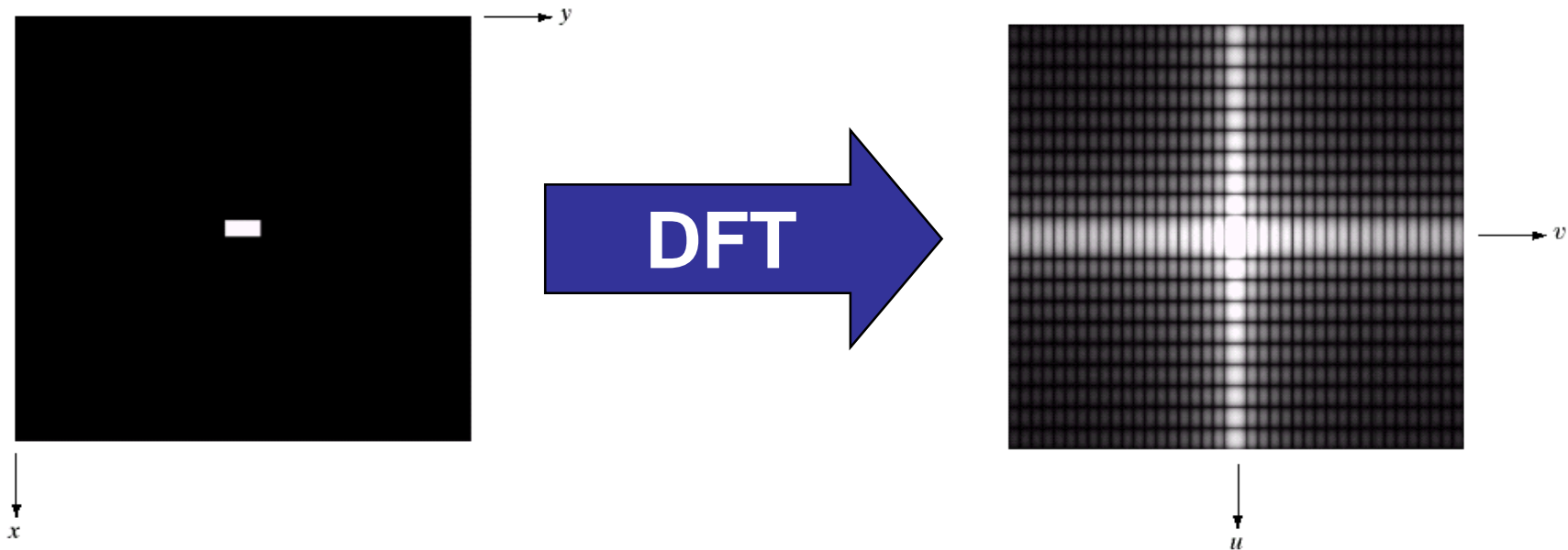
The Discrete Fourier Transform (DFT)

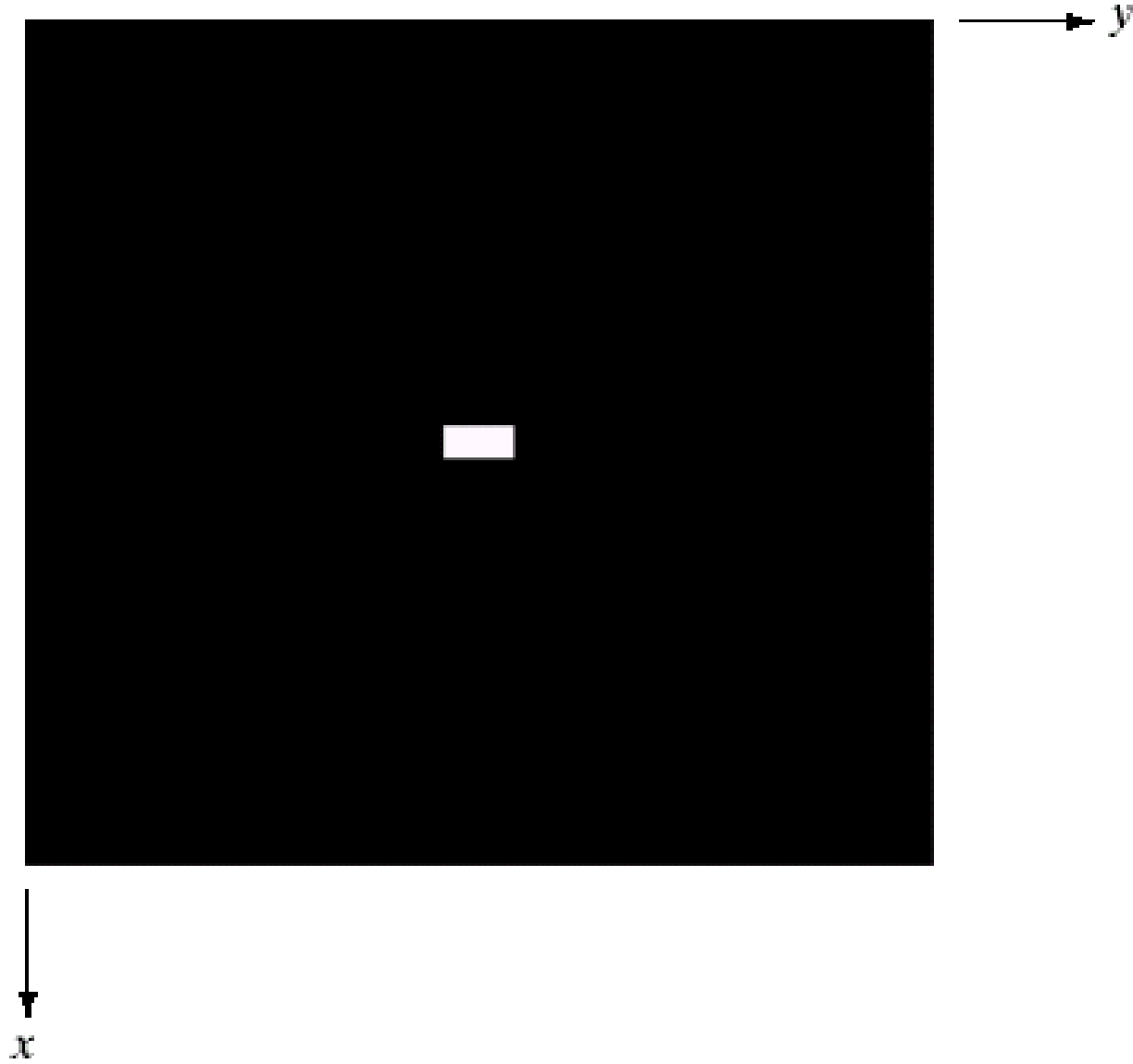
The *Discrete Fourier Transform* of $f(x, y)$, for $x = 0, 1, 2 \dots M-1$ and $y = 0, 1, 2 \dots N-1$, denoted by $F(u, v)$, is given by the equation:

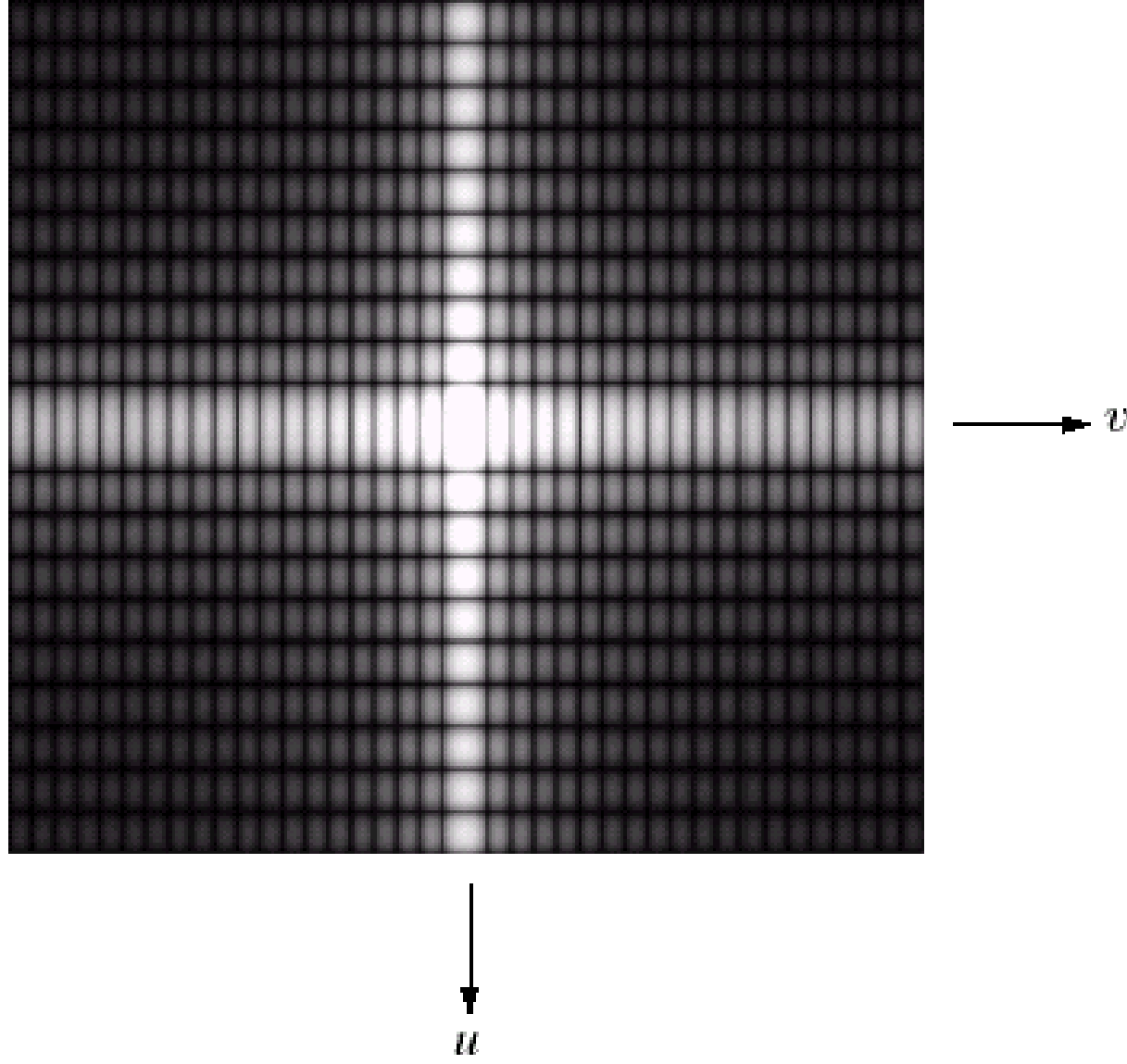
$$F(u, v) = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x, y) e^{-j2\pi(ux/M + vy/N)}$$

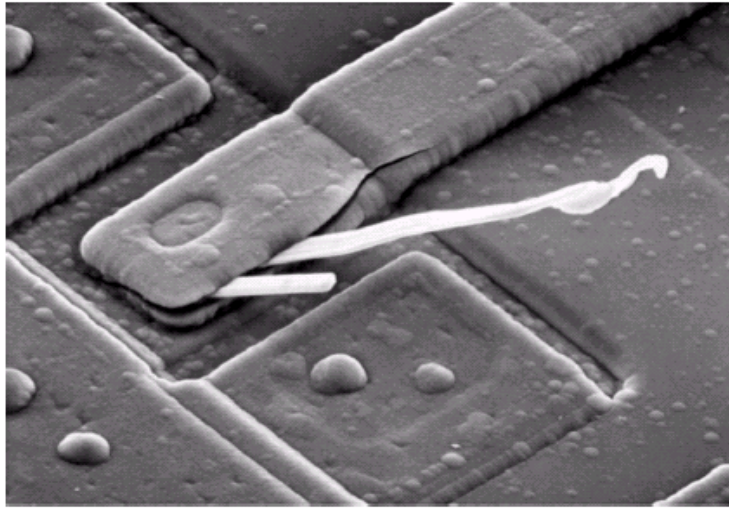
for $u = 0, 1, 2 \dots M-1$ and $v = 0, 1, 2 \dots N-1$.

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

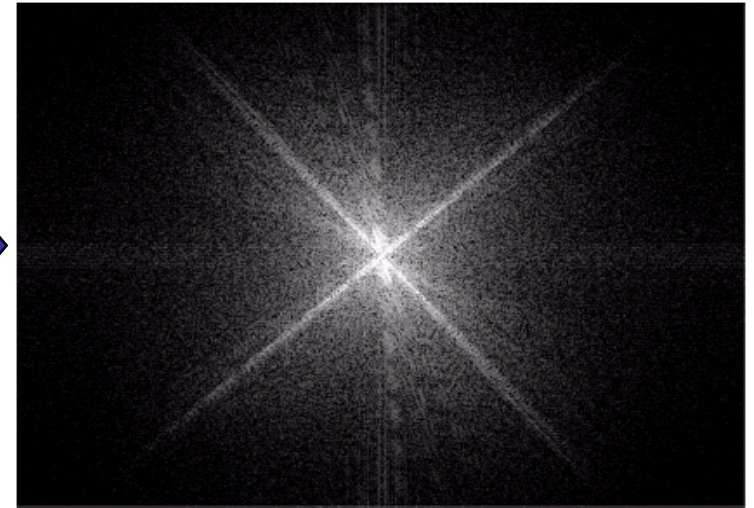






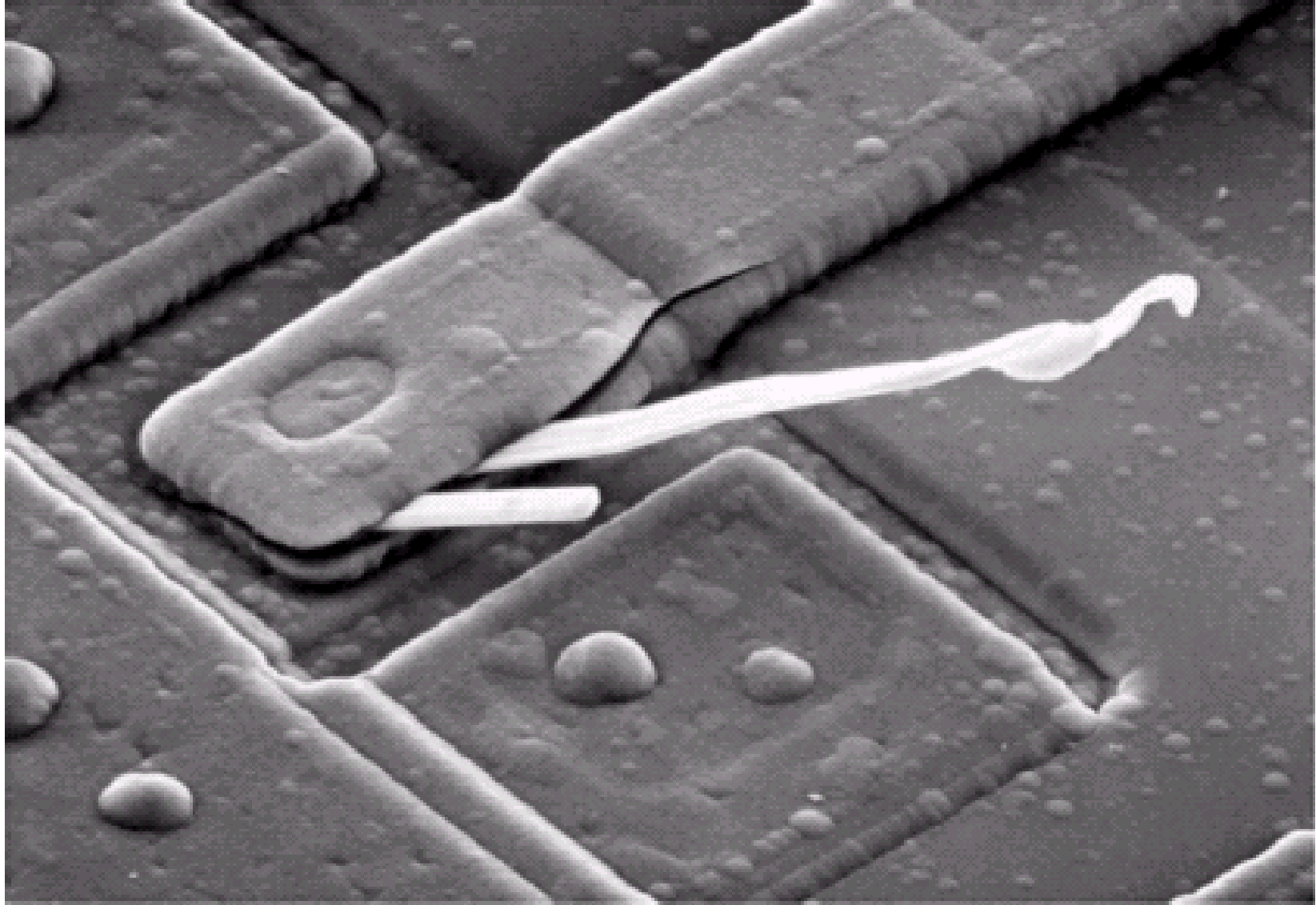


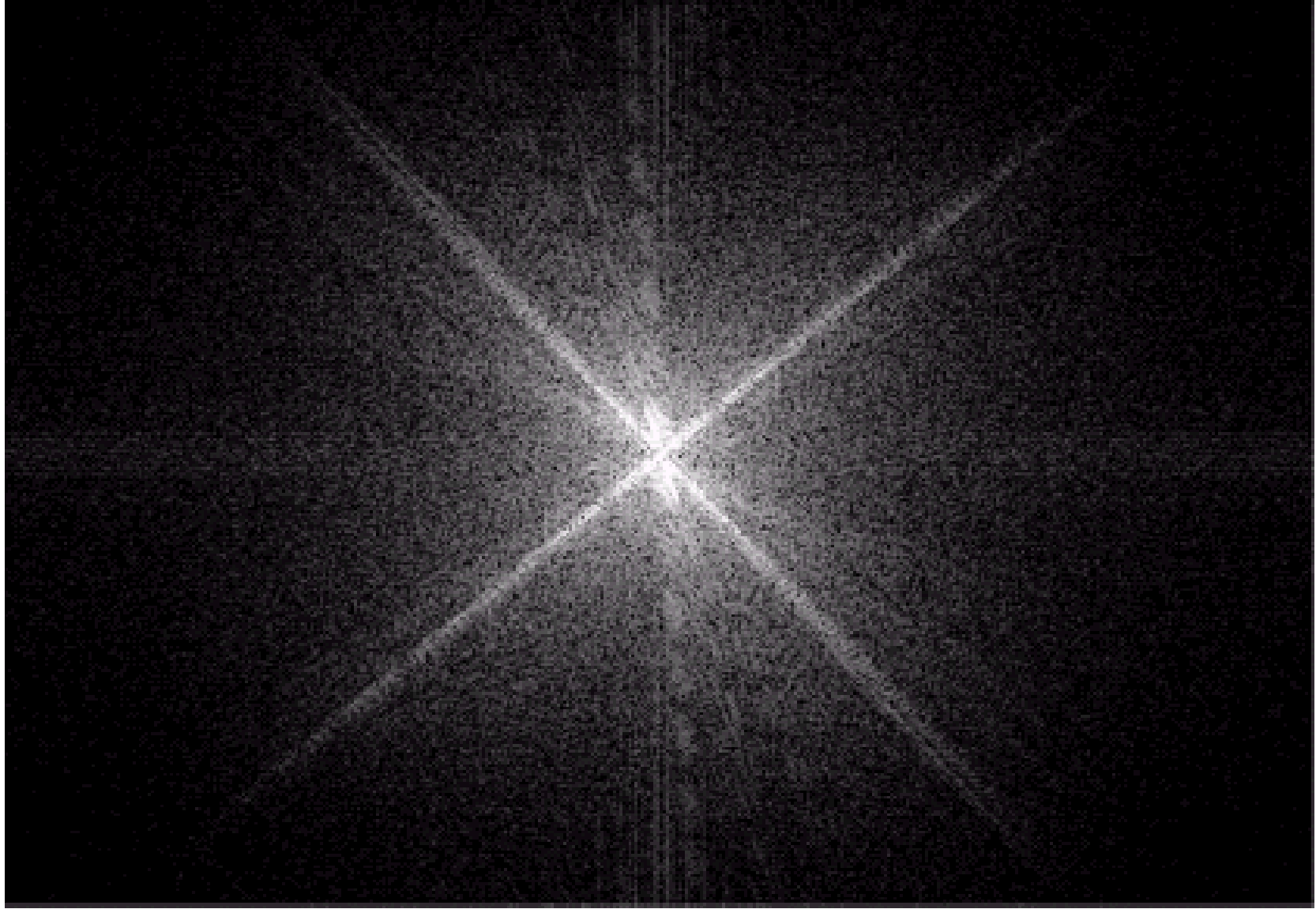
Scanning electron microscope image of an integrated circuit magnified ~2500 times



Fourier spectrum of the image

DFT & Images (cont...)





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

The inverse DFT is given by:

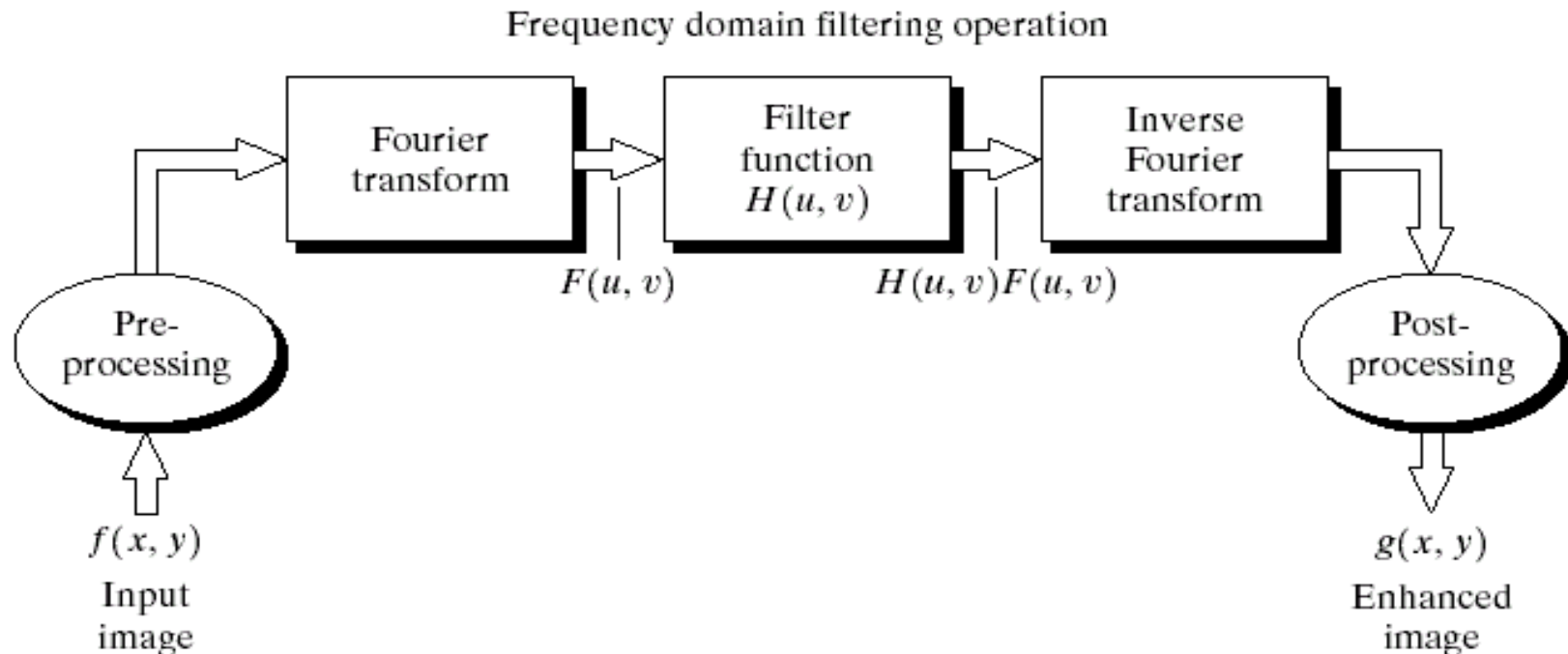
$$f(x, y) = \frac{1}{MN} \sum_{u=0}^{M-1} \sum_{v=0}^{N-1} F(u, v) e^{j2\pi(ux/M + vy/N)}$$

for $x = 0, 1, 2 \dots M-1$ and $y = 0, 1, 2 \dots N-1$

The DFT and Image Processing

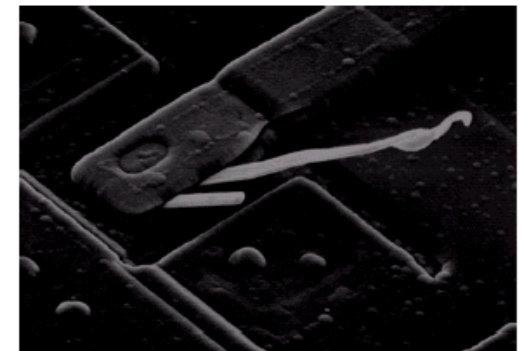
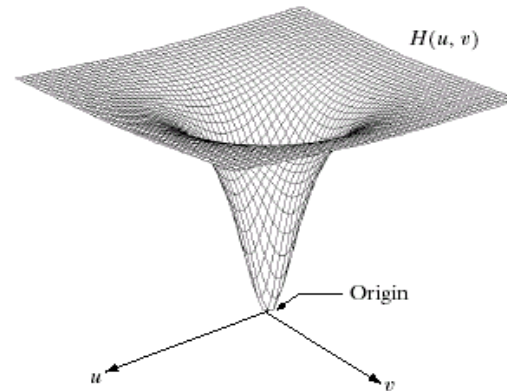
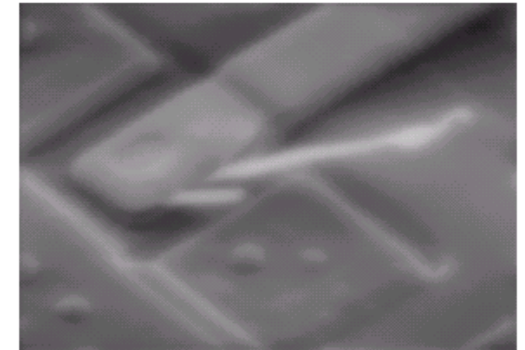
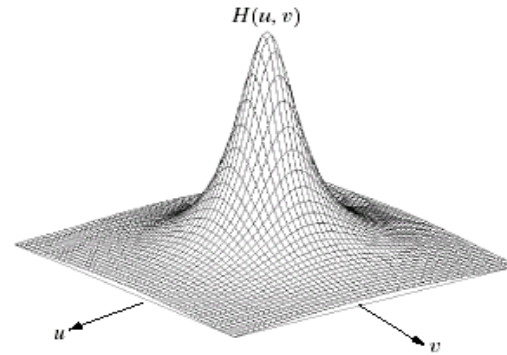
To filter an image in the frequency domain:

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

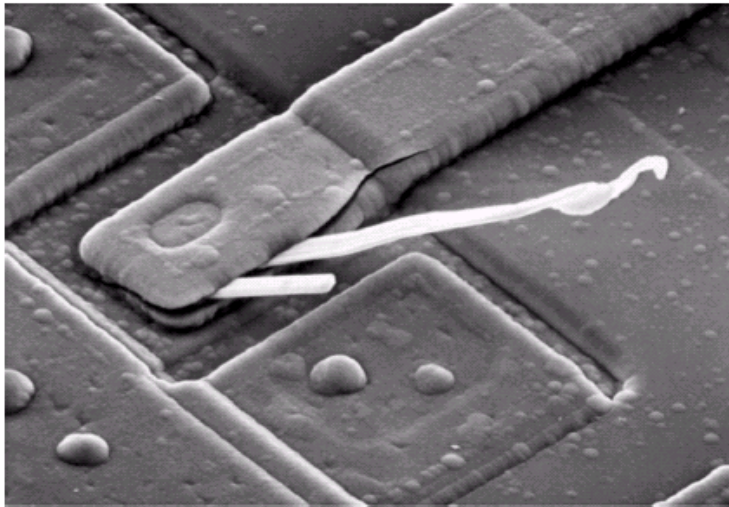


Some Basic Frequency Domain Filters

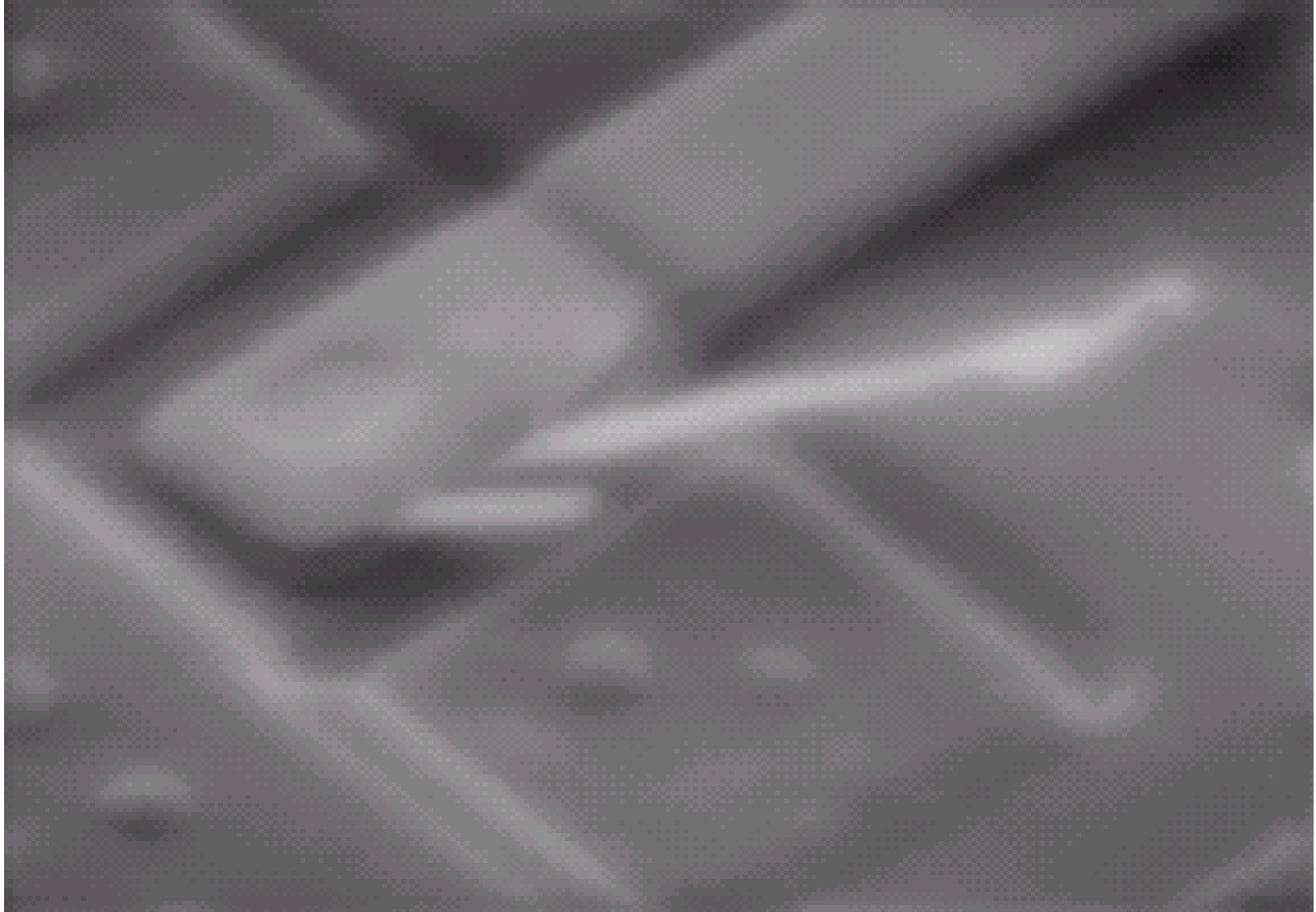
Low Pass Filter



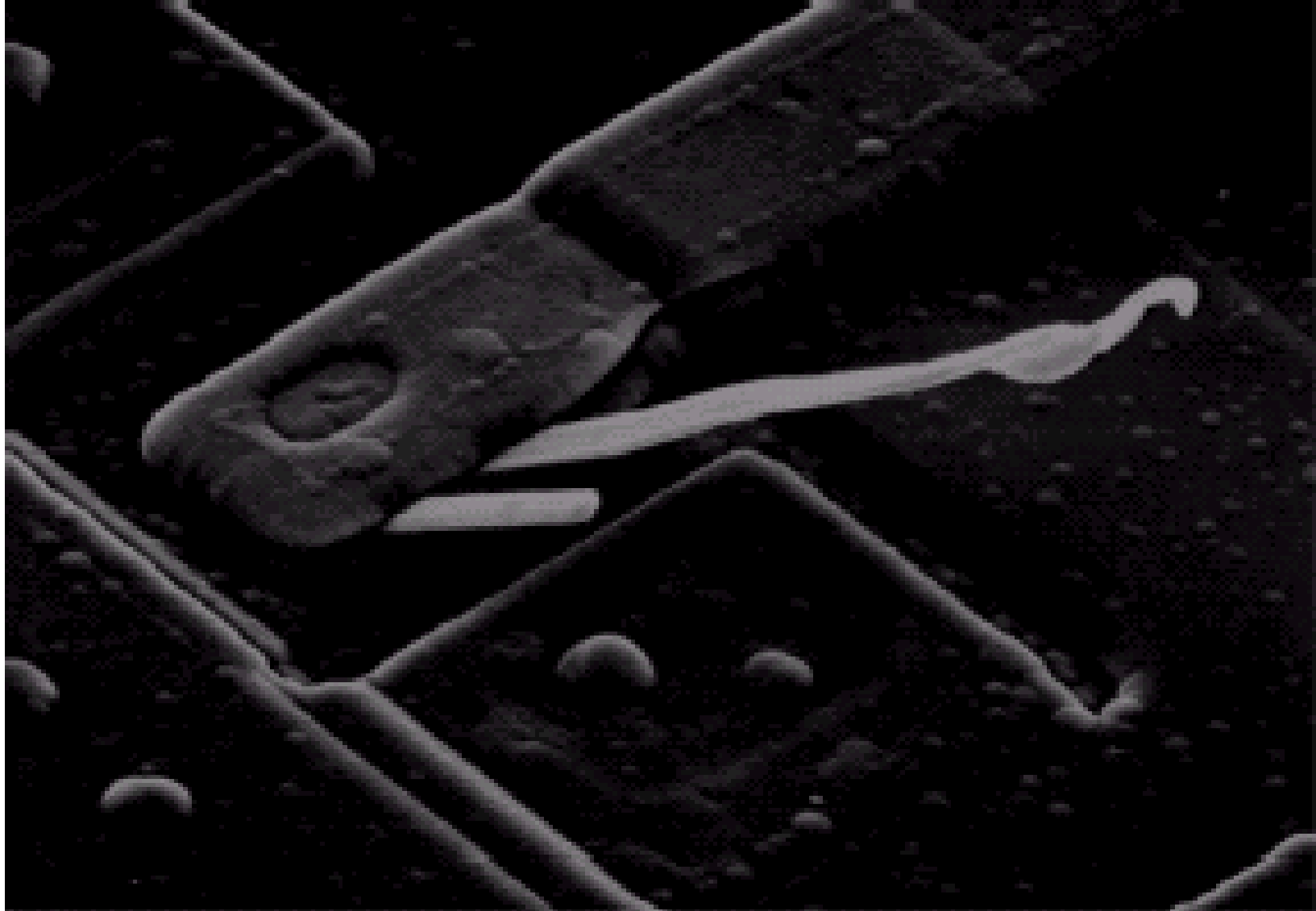
High Pass Filter



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

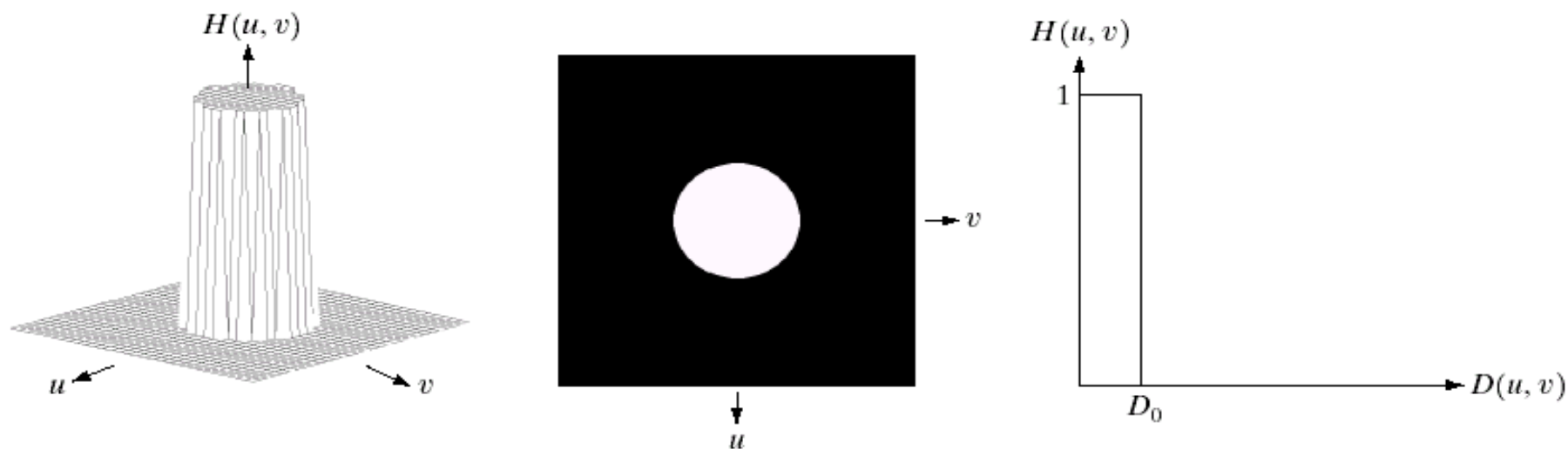
The basic model for filtering is:

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

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

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



changing the distance changes the behaviour of the filter

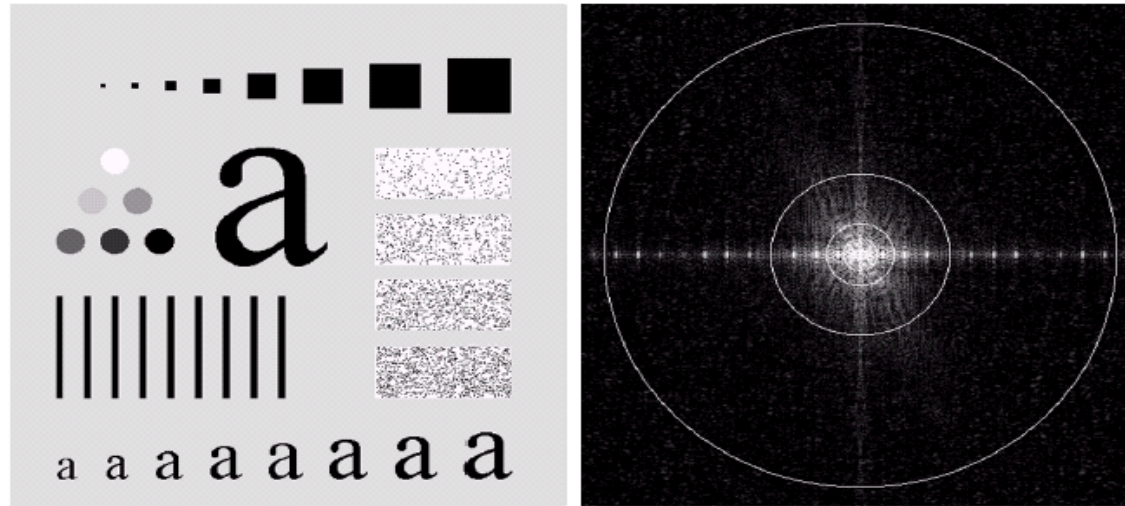
The transfer function for the ideal low pass filter can be given as:

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

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

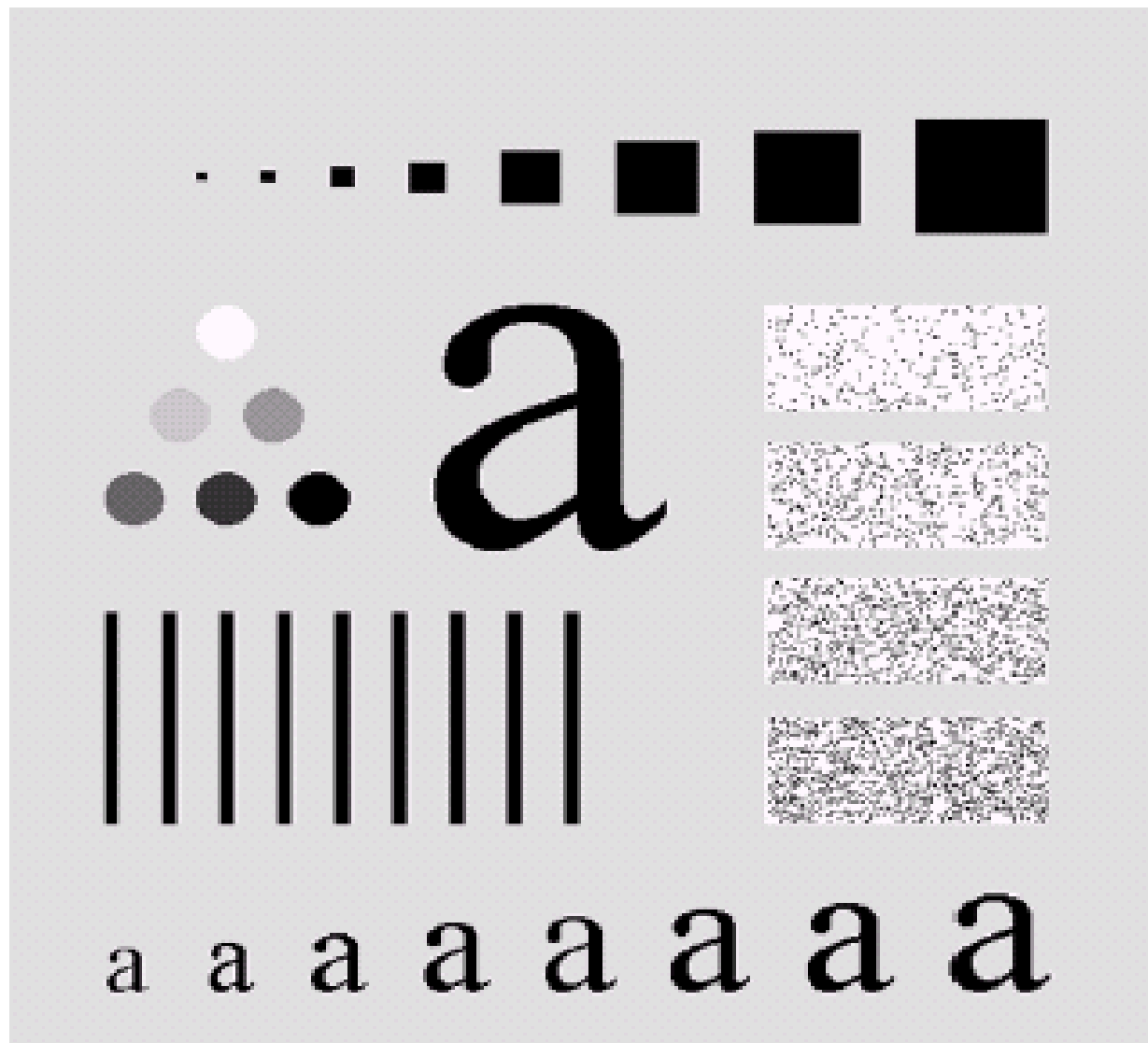
$$D(u, v) = [(u - M / 2)^2 + (v - N / 2)^2]^{1/2}$$

Ideal Low Pass Filter (cont...)

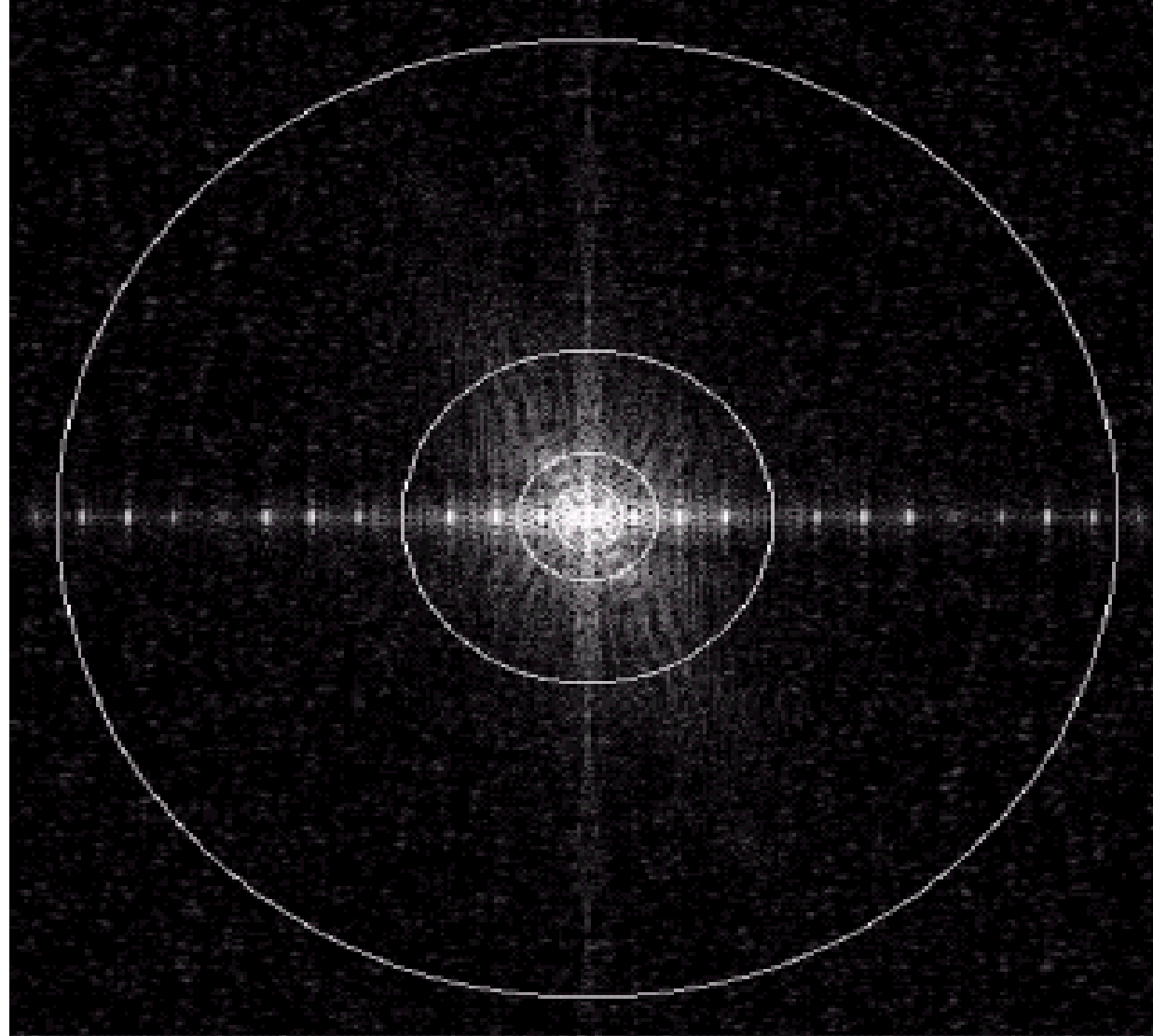


Above we show an image, its Fourier spectrum and a series of ideal low pass filters of radius 5, 15, 30, 80 and 230 superimposed on top of it

Ideal Low Pass Filter (cont...)

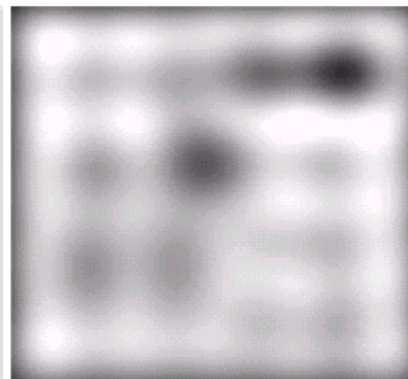
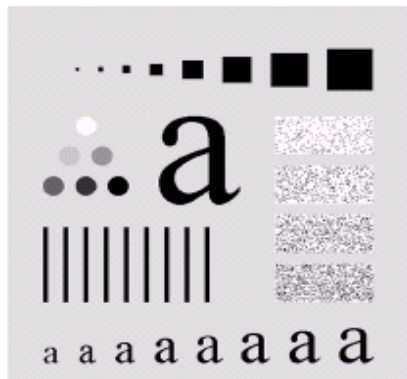


Ideal Low Pass Filter (cont...)



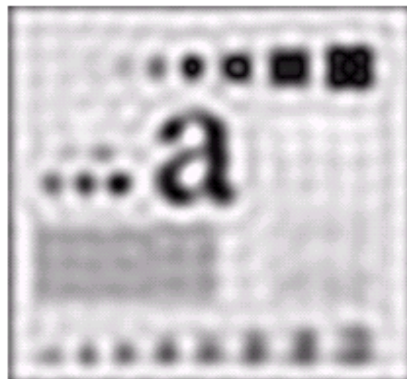
Ideal Low Pass Filter (cont...)

Original image



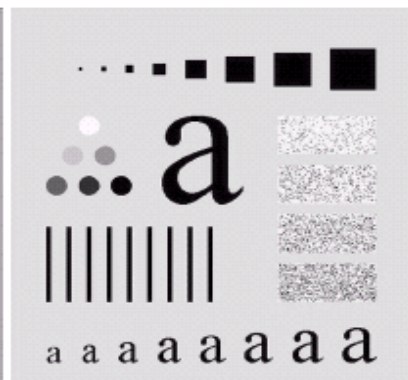
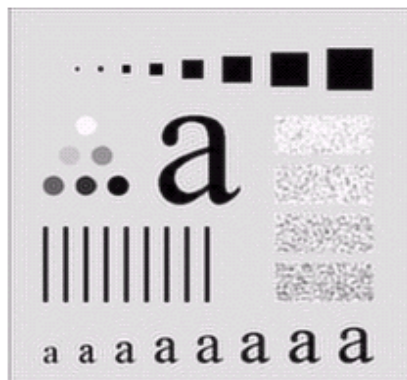
Result of filtering with ideal low pass filter of radius 5

Result of filtering with ideal low pass filter of radius 15



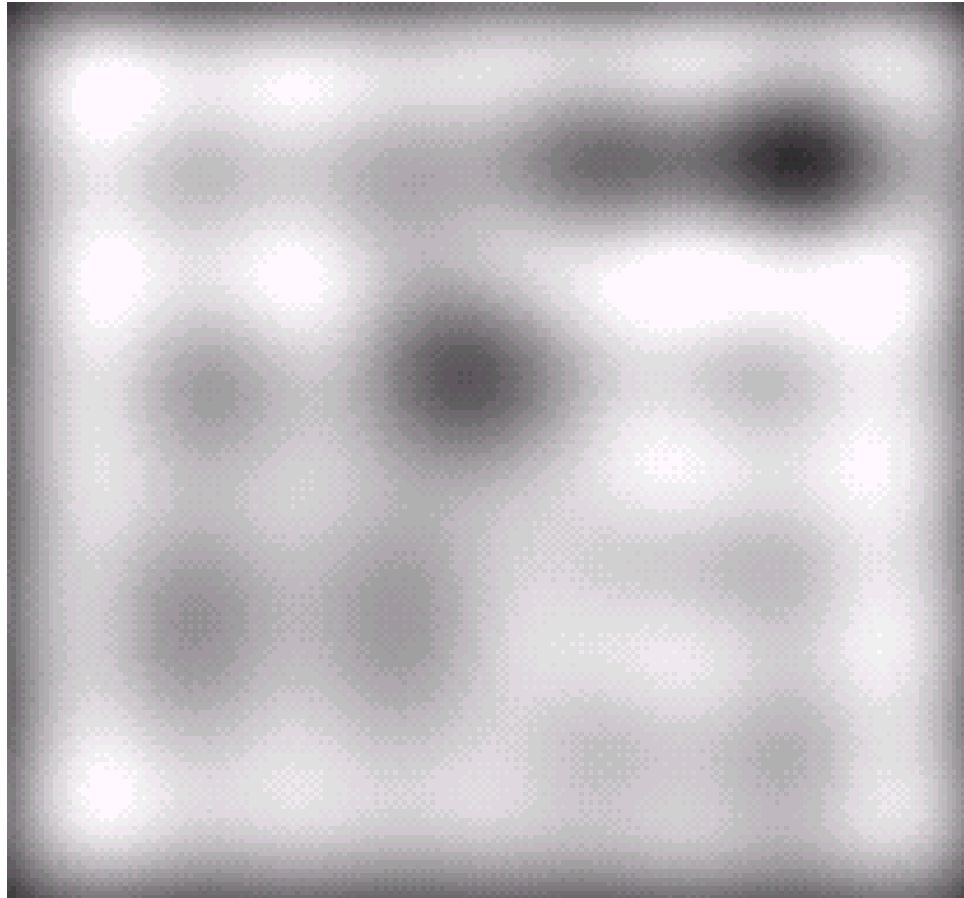
Result of filtering with ideal low pass filter of radius 30

Result of filtering with ideal low pass filter of radius 80



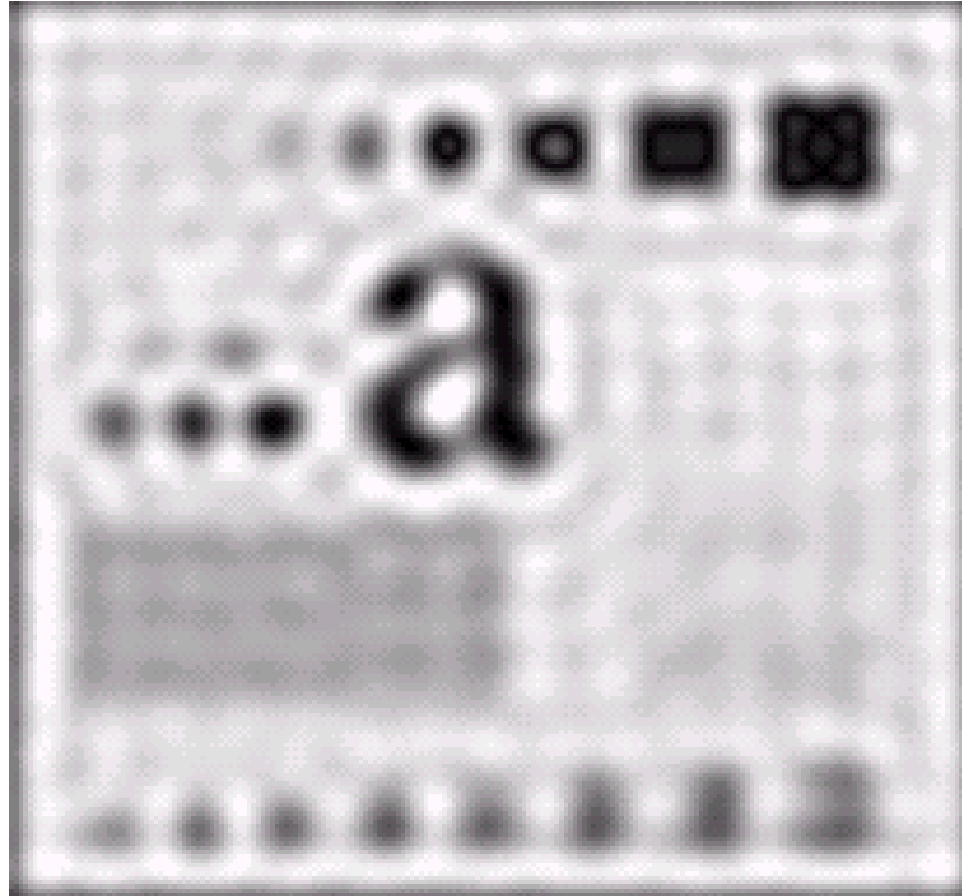
Result of filtering with ideal low pass filter of radius 230

Ideal Low Pass Filter (cont...)



Result of filtering
with ideal low pass
filter of radius 5

Ideal Low Pass Filter (cont...)

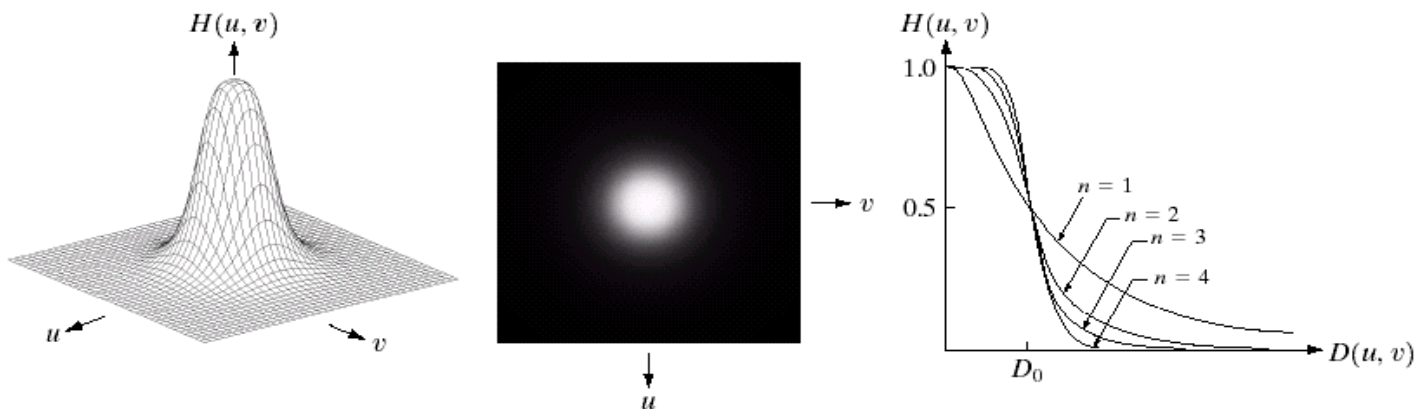


Result of filtering
with ideal low pass
filter of radius 15

Butterworth Lowpass Filters

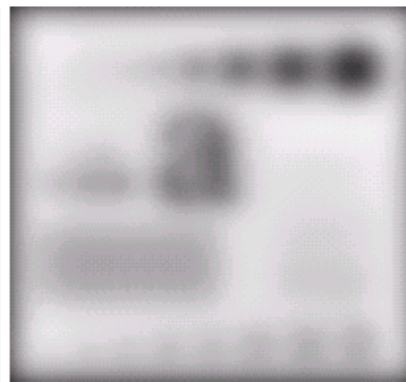
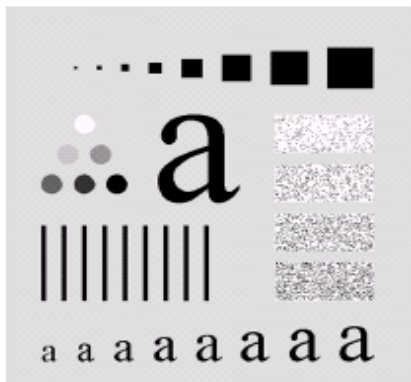
The transfer function of a Butterworth lowpass filter of order n with cutoff frequency at distance D_0 from the origin is defined as:

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



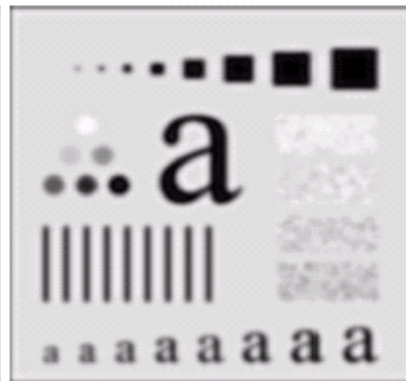
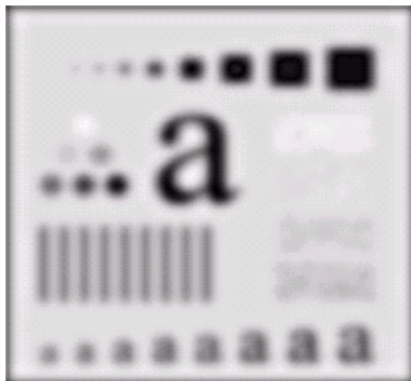
Butterworth Lowpass Filter (cont...)

Original image



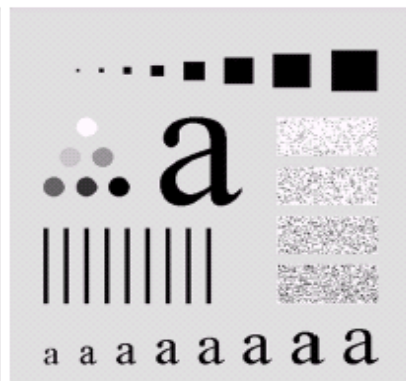
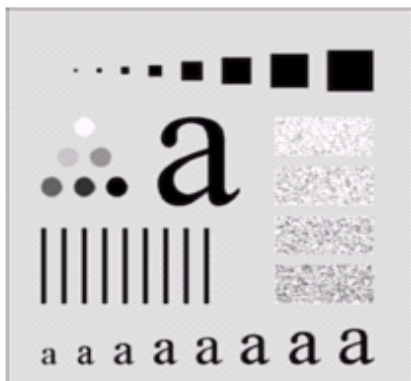
Result of filtering with Butterworth filter of order 2 and cutoff radius 5

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



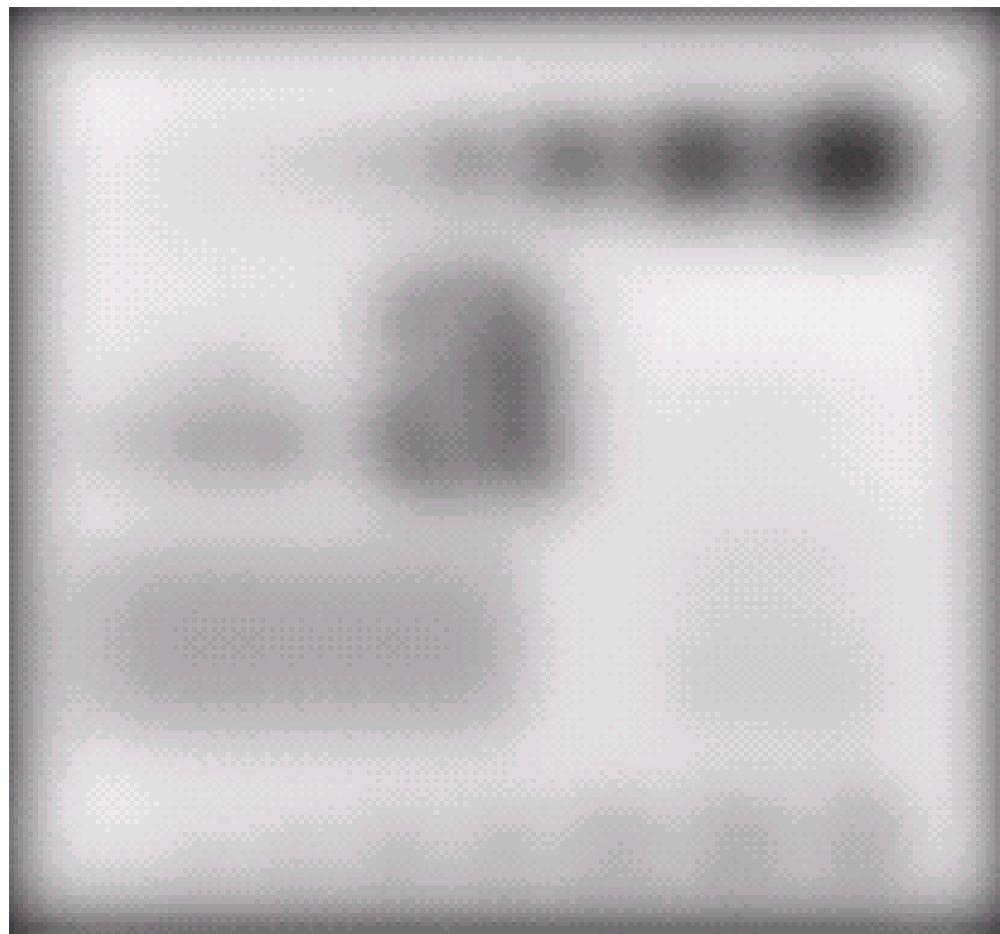
Result of filtering with Butterworth filter of order 2 and cutoff radius 30

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

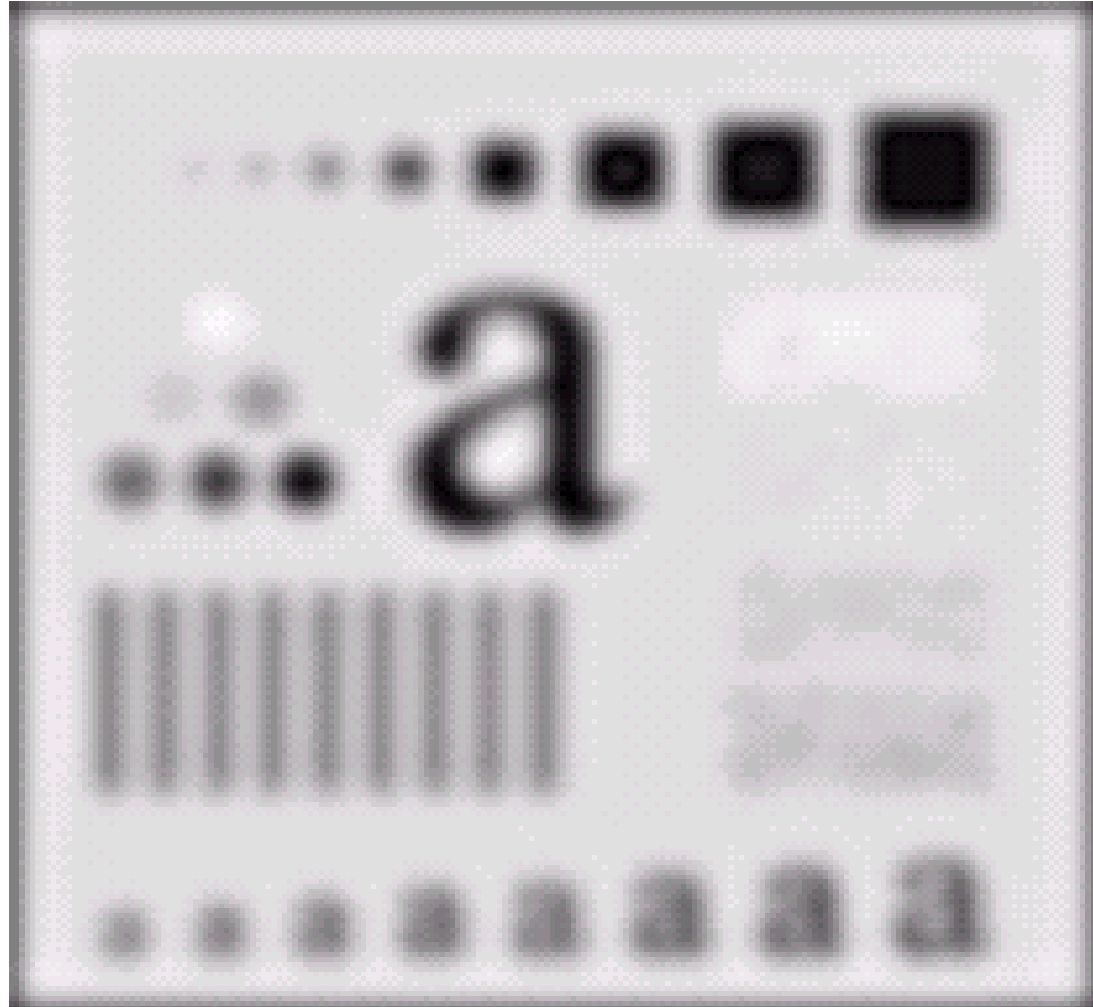
Butterworth Lowpass Filter (cont...)



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

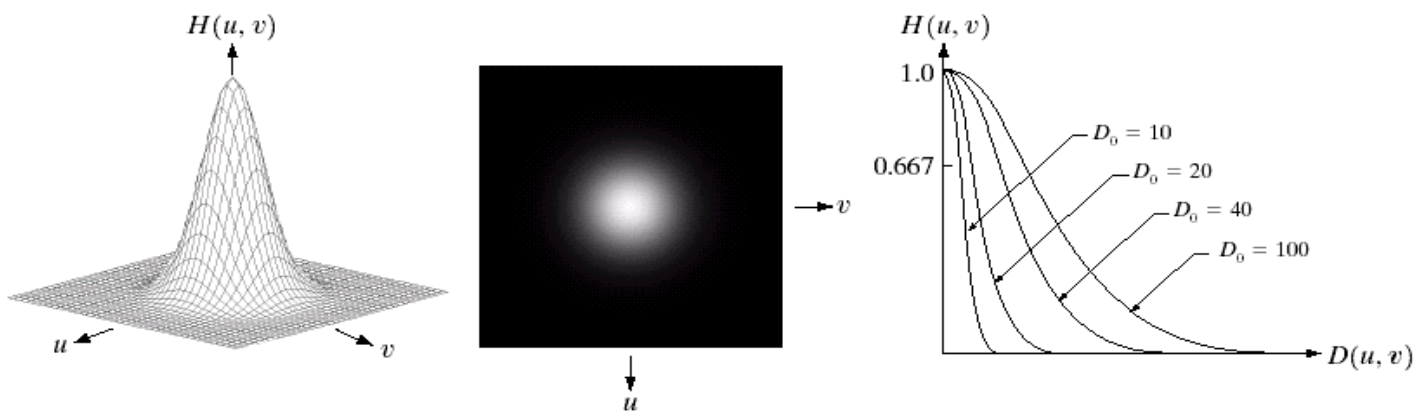
Butterworth Lowpass Filter (cont...)

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



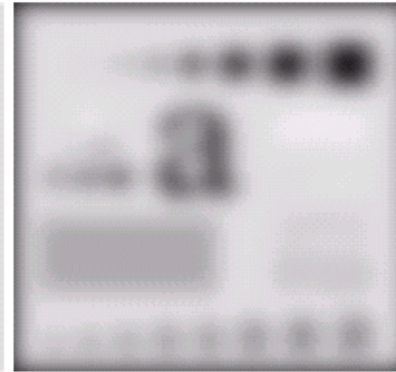
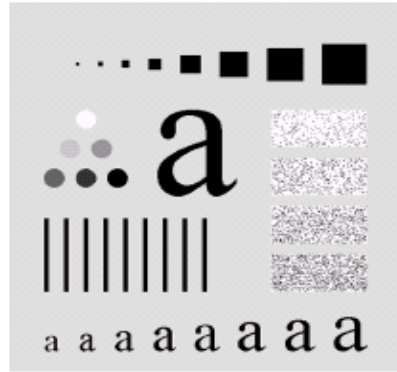
The transfer function of a Gaussian lowpass filter is defined as:

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



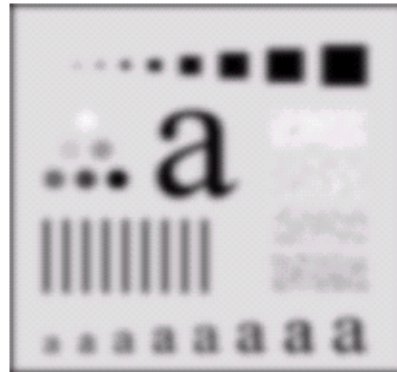
Gaussian Lowpass Filters (cont...)

Original image



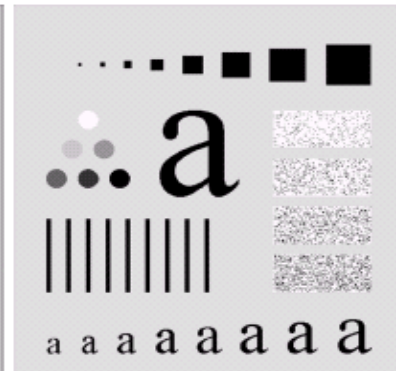
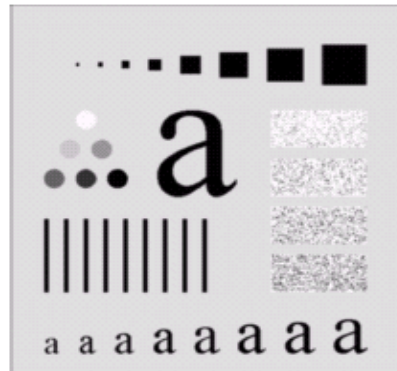
Result of filtering with Gaussian filter with cutoff radius 5

Result of filtering with Gaussian filter with cutoff radius 15



Result of filtering with Gaussian filter with cutoff radius 30

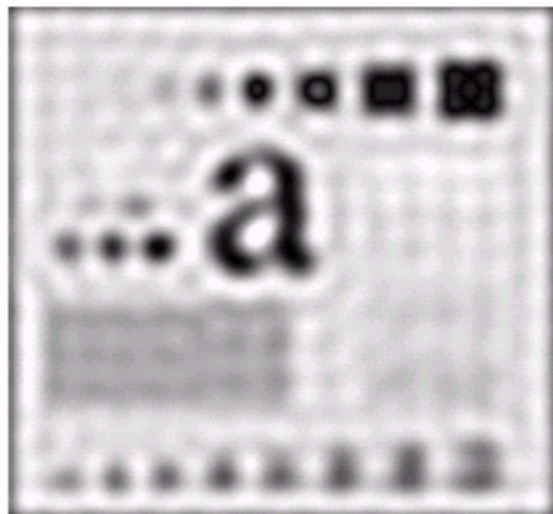
Result of filtering with Gaussian filter with cutoff radius 85



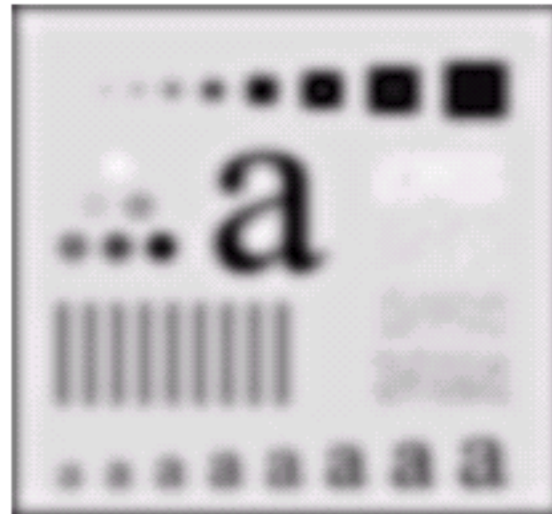
Result of filtering with Gaussian filter with cutoff radius 230

Lowpass Filters Compared

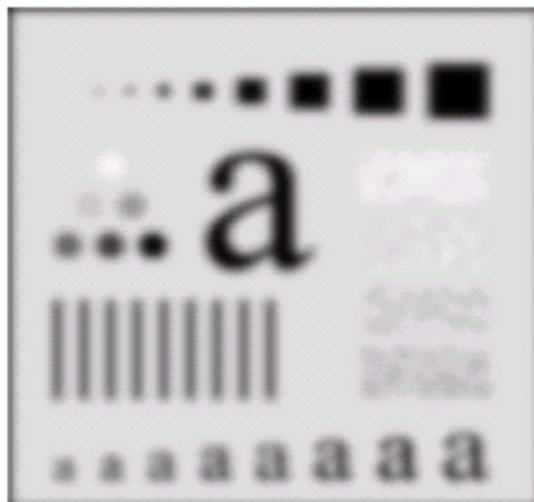
Result of filtering
with ideal low pass
filter of radius 15



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



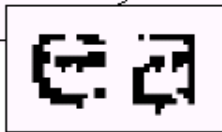
Result of filtering
with Gaussian
filter with cutoff
radius 15



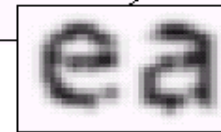
Lowpass Filtering Examples

A low pass Gaussian filter is used to connect broken text

Historically, certain computer programs were written using only two digits rather than four to define the applicable year. Accordingly, the company's software may recognize a date using "00" as 1900 rather than the year 2000.

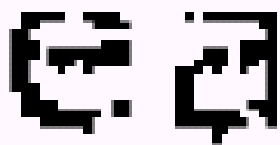


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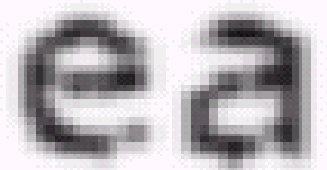


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Lowpass Filtering Examples (cont...)

Different lowpass Gaussian filters used to remove blemishes in a photograph

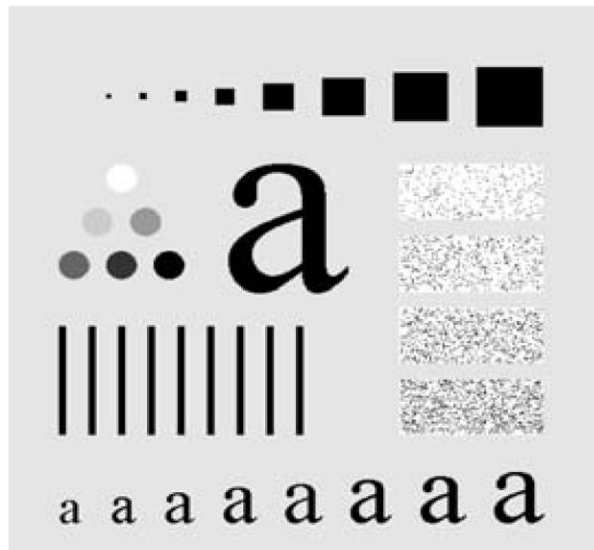


Lowpass Filtering Examples (cont...)

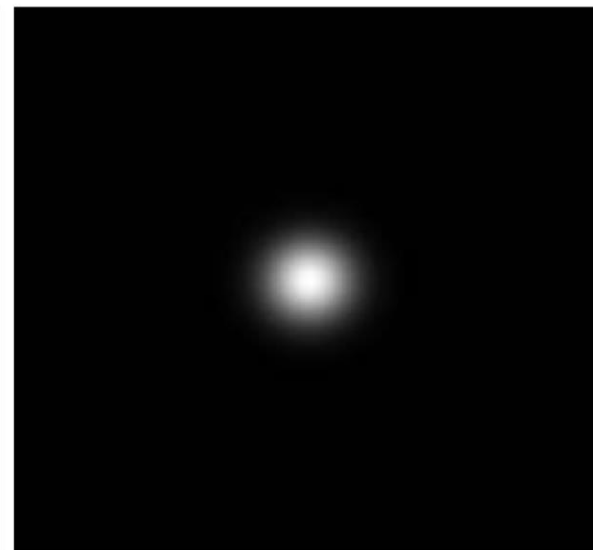


Lowpass Filtering Examples (cont...)

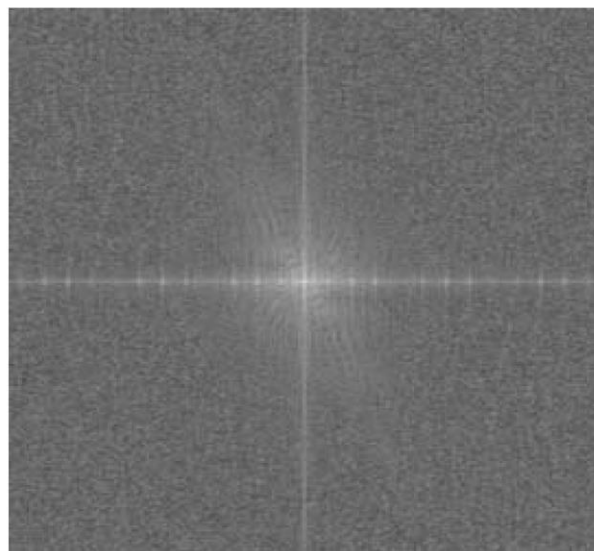
Original
image



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

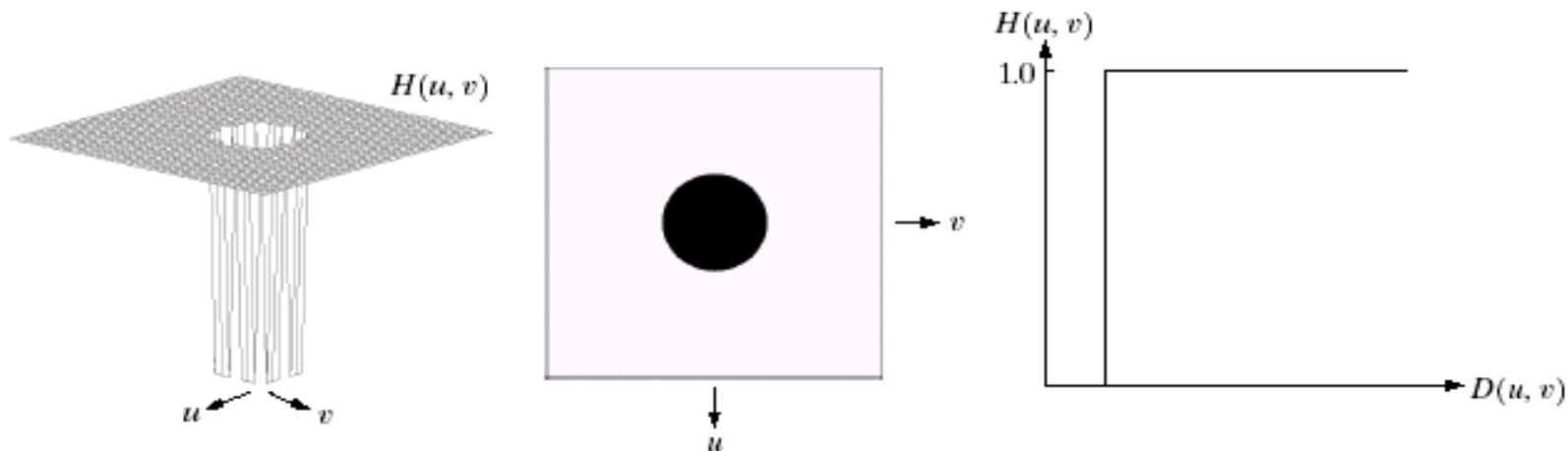
High pass frequencies are precisely the reverse of low pass filters, so:

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

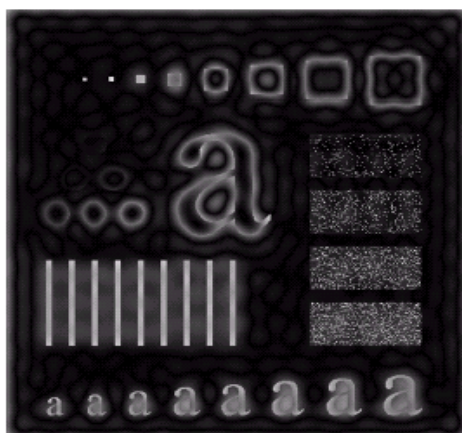
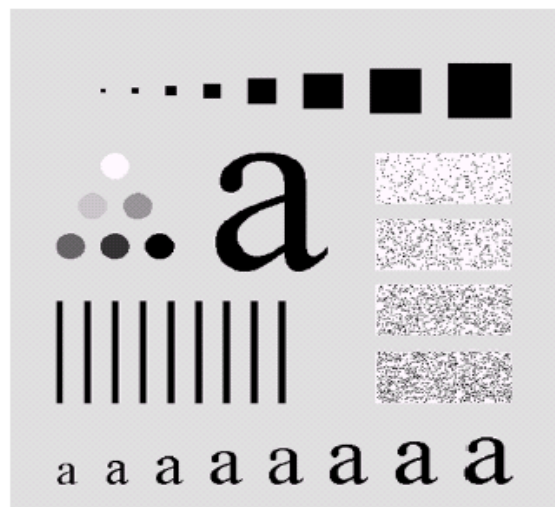
The ideal high pass filter is given as:

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

where D_0 is the cut off distance as before



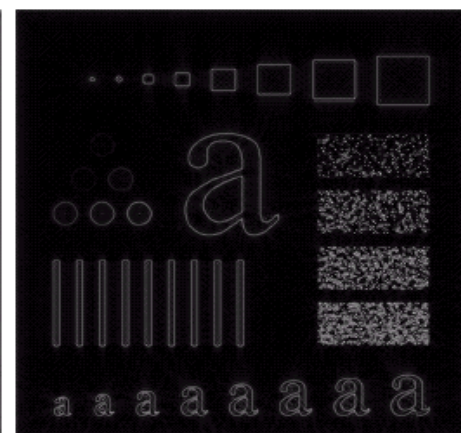
Ideal High Pass Filters (cont...)



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



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



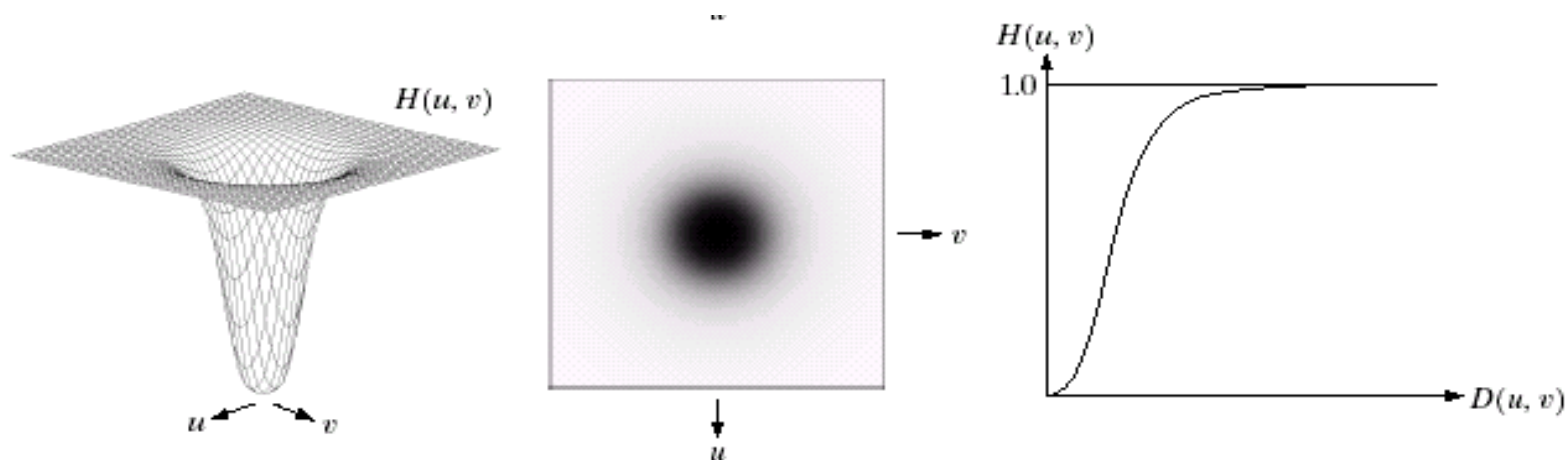
Results of ideal
high pass filtering
with $D_0 = 80$

Butterworth High Pass Filters

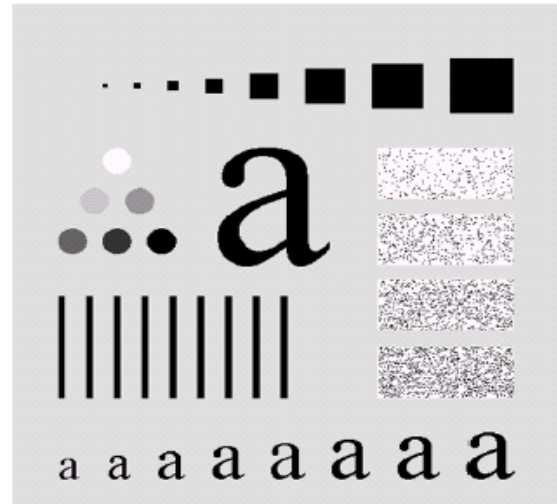
The Butterworth high pass filter is given as:

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

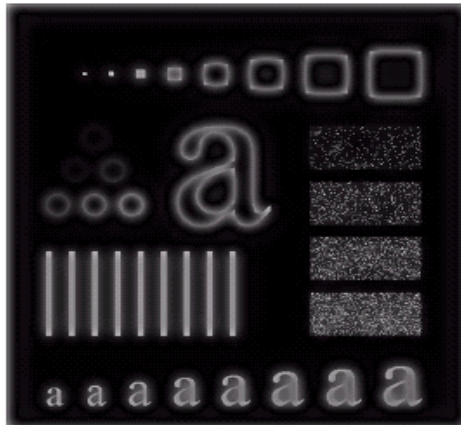
where n is the order and D_0 is the cut off distance as before



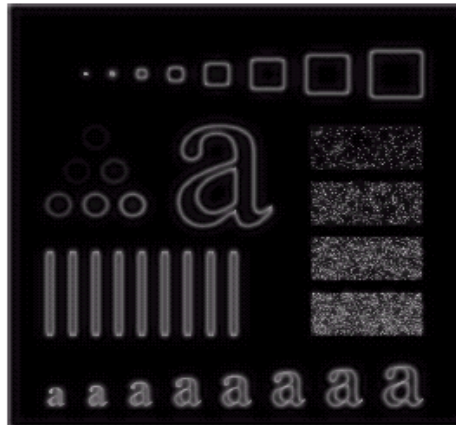
Butterworth High Pass Filters (cont...)



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



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



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

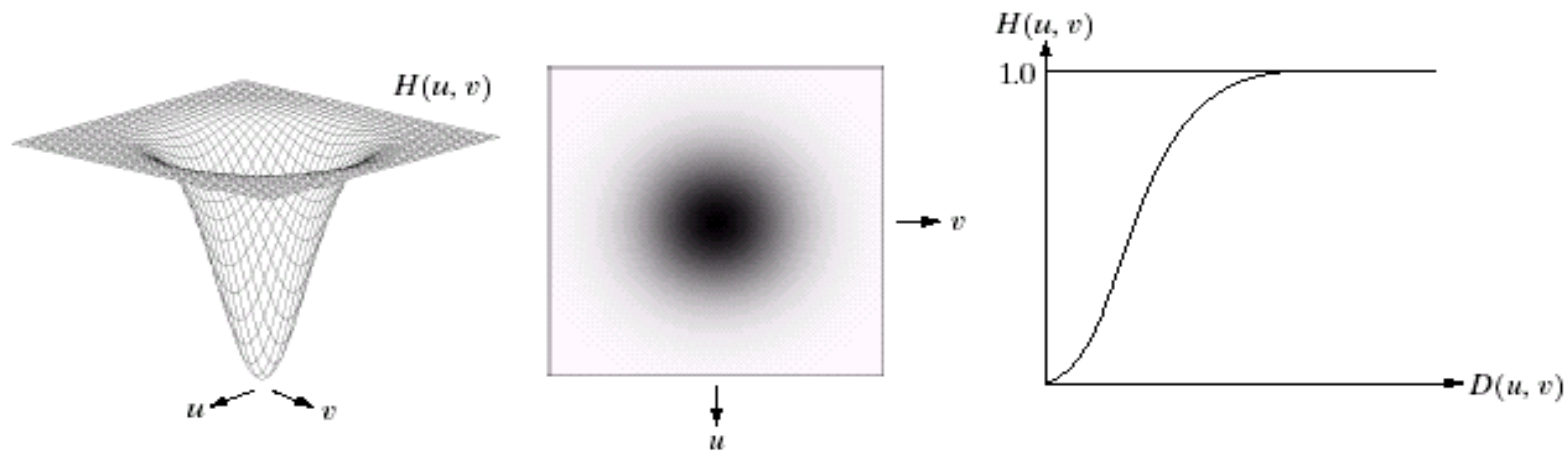


Gaussian High Pass Filters

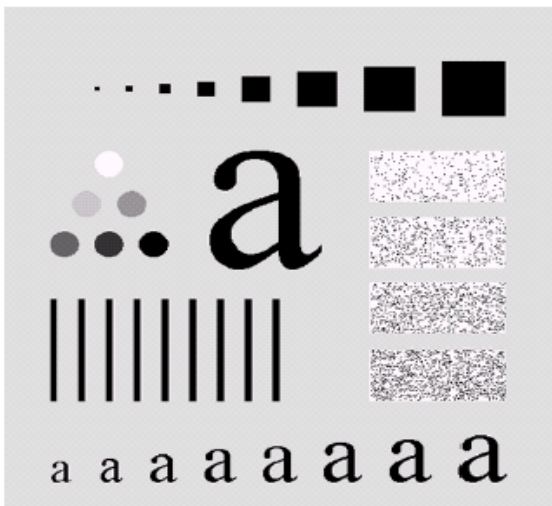
The Gaussian high pass filter is given as:

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

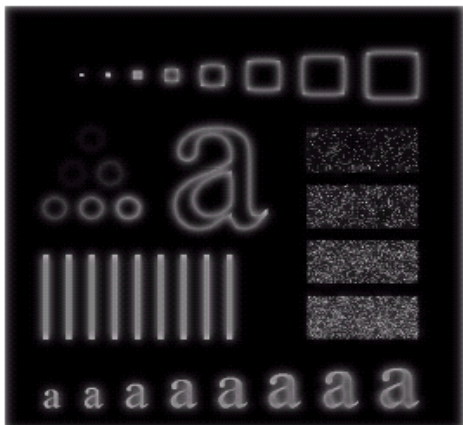
where D_0 is the cut off distance as before



Gaussian High Pass Filters (cont...)



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



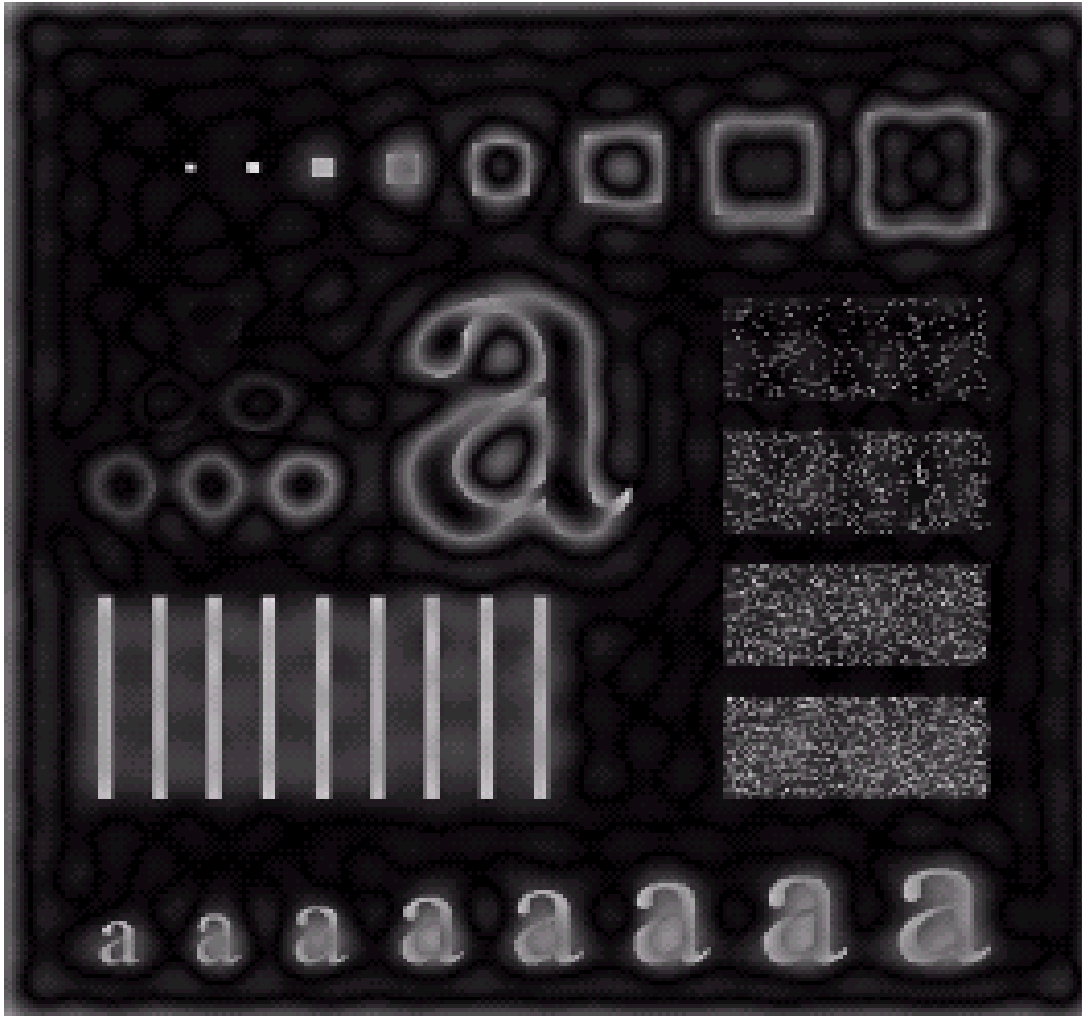
Results of Gaussian high pass filtering with $D_0 = 30$



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

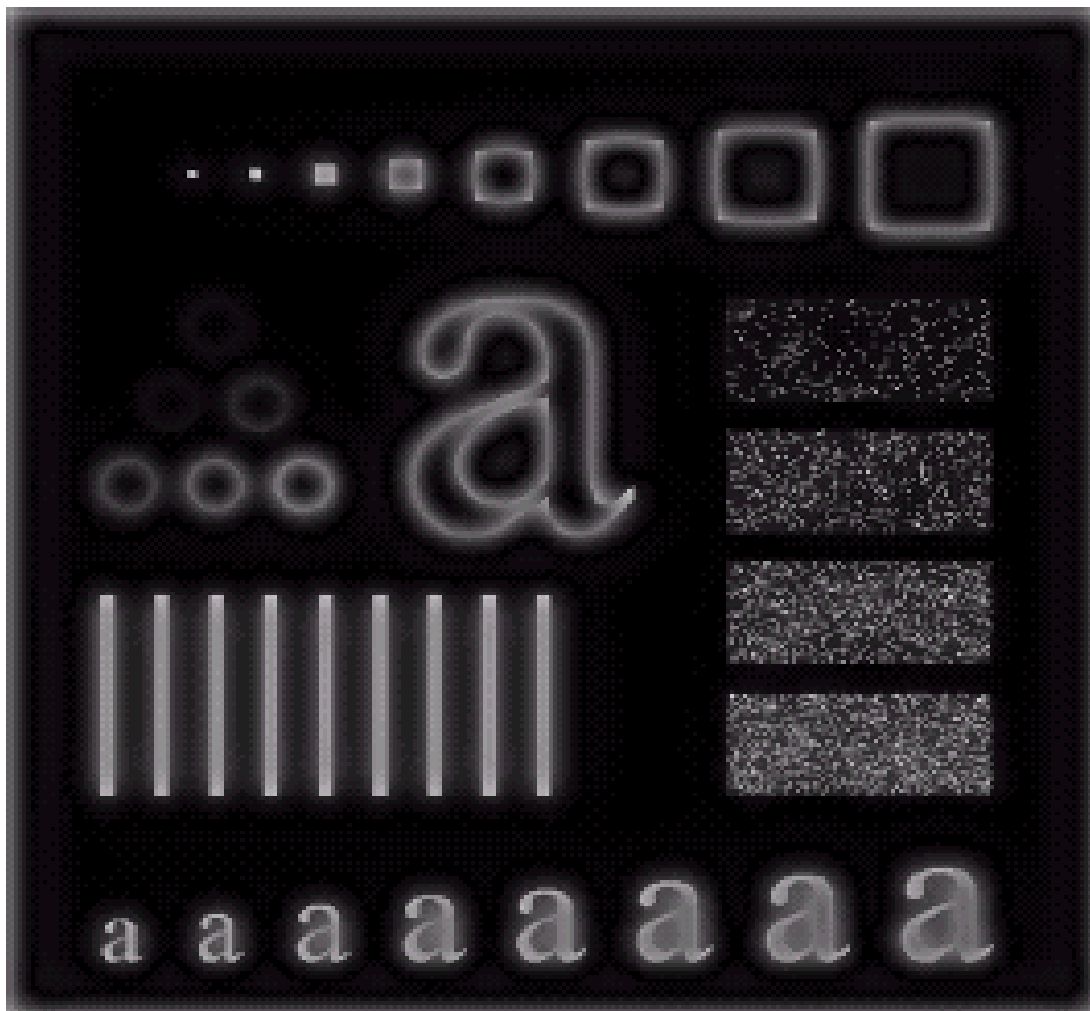


Highpass Filter Comparison



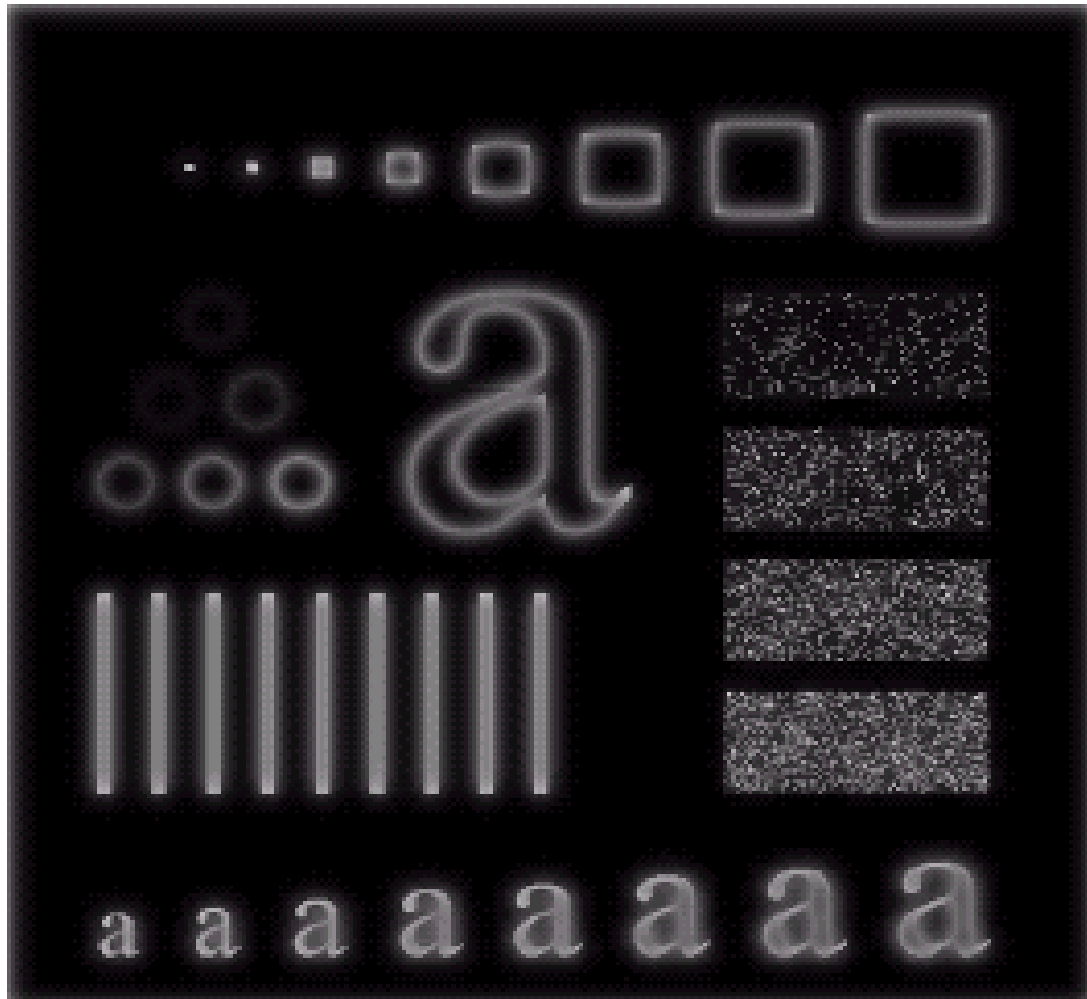
Results of ideal
high pass filtering
with $D_0 = 15$

Highpass Filter Comparison



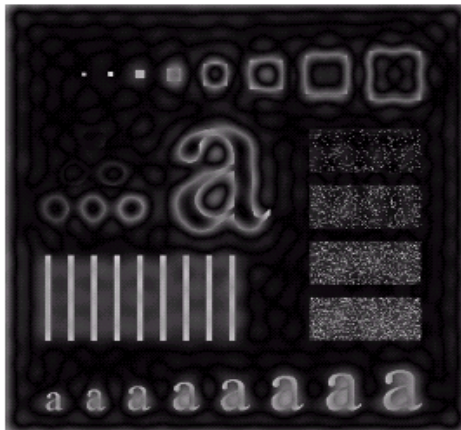
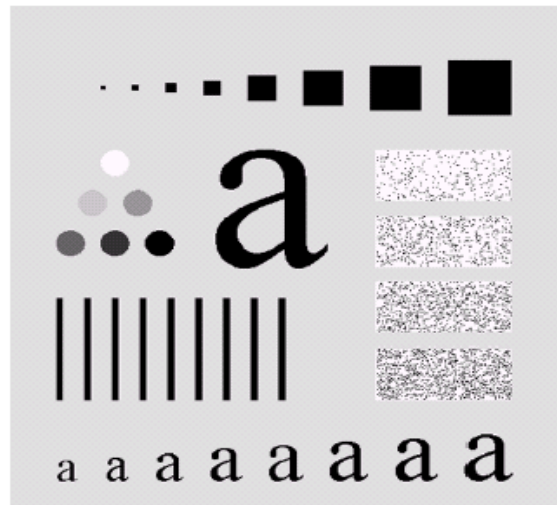
Results of Butterworth
high pass filtering of order
2 with $D_0 = 15$

Highpass Filter Comparison

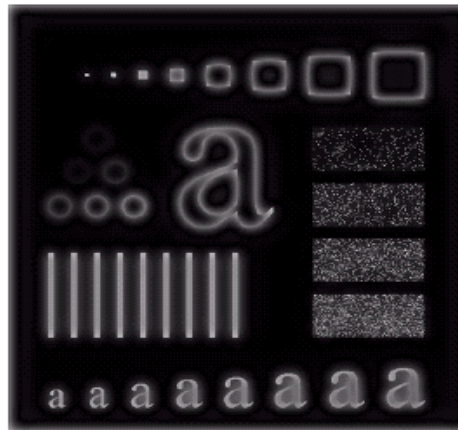


Results of Gaussian
high pass filtering with
 $D_0 = 15$

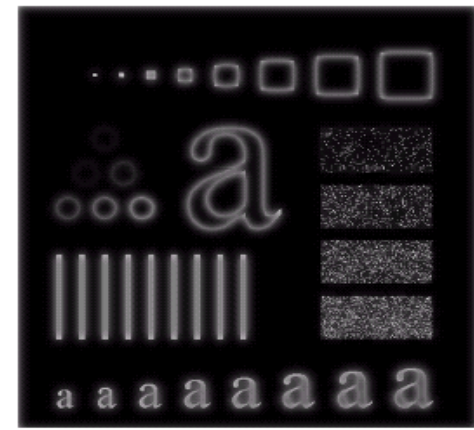
Highpass Filter Comparison



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

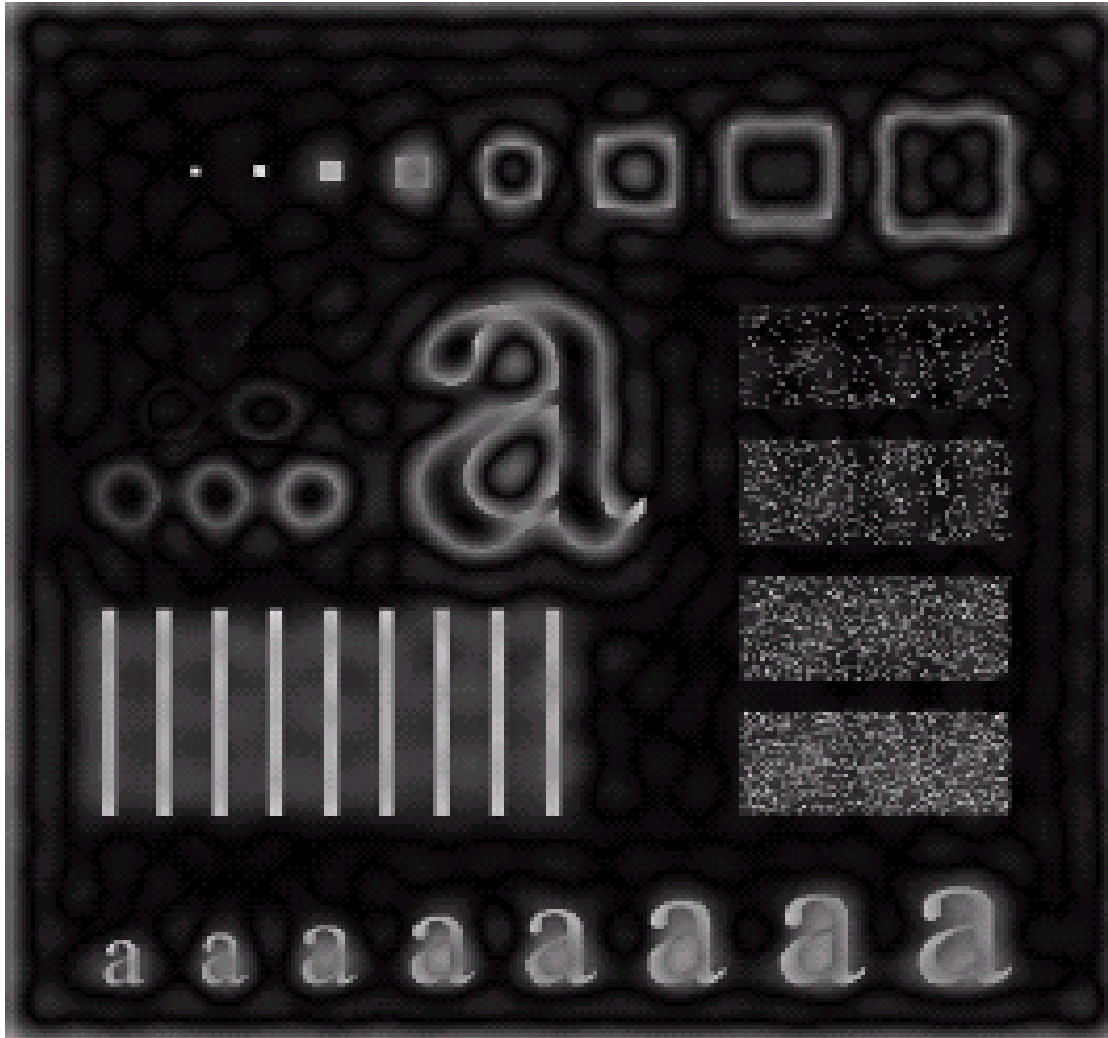


Results of Butterworth
high pass filtering of order
2 with $D_0 = 15$



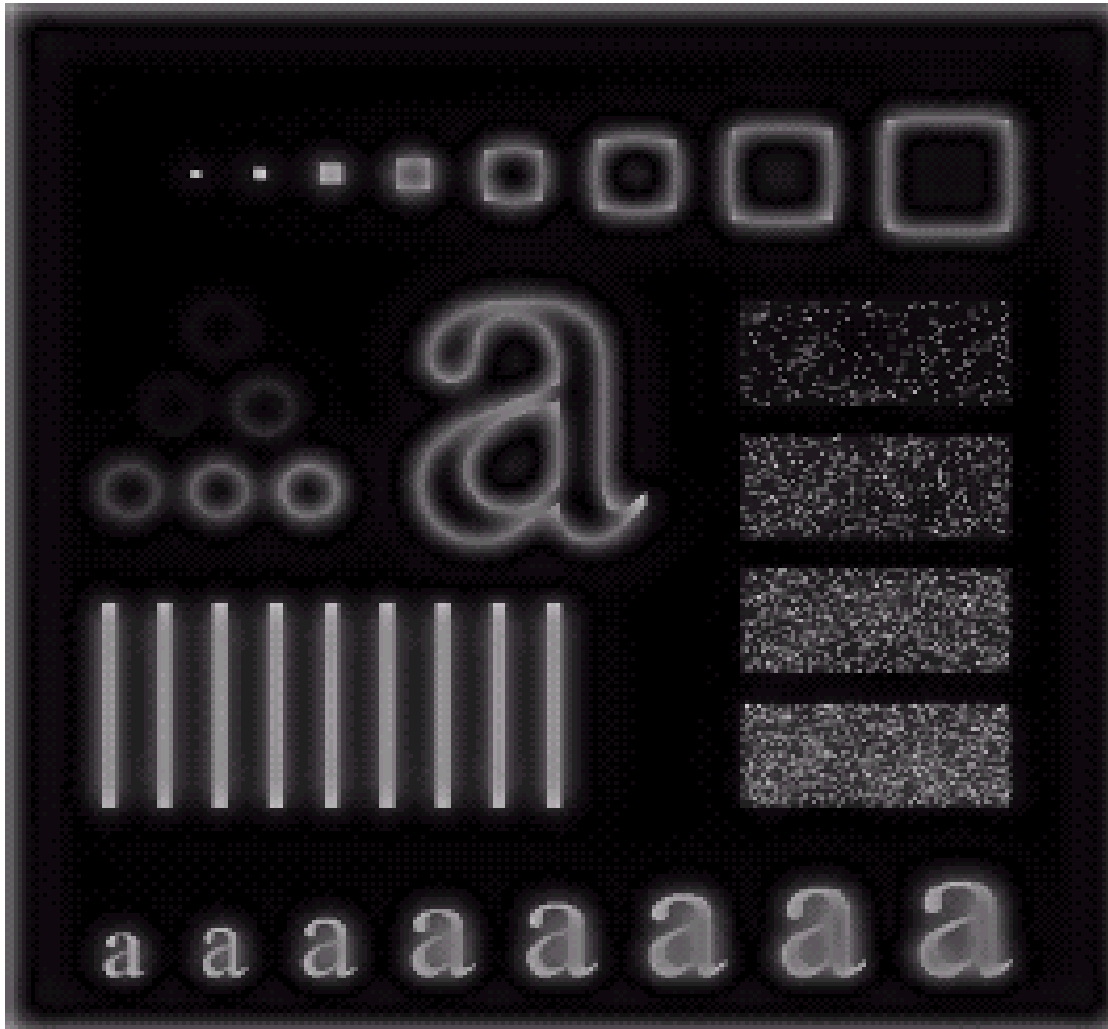
Results of Gaussian
high pass filtering with
 $D_0 = 15$

Highpass Filter Comparison



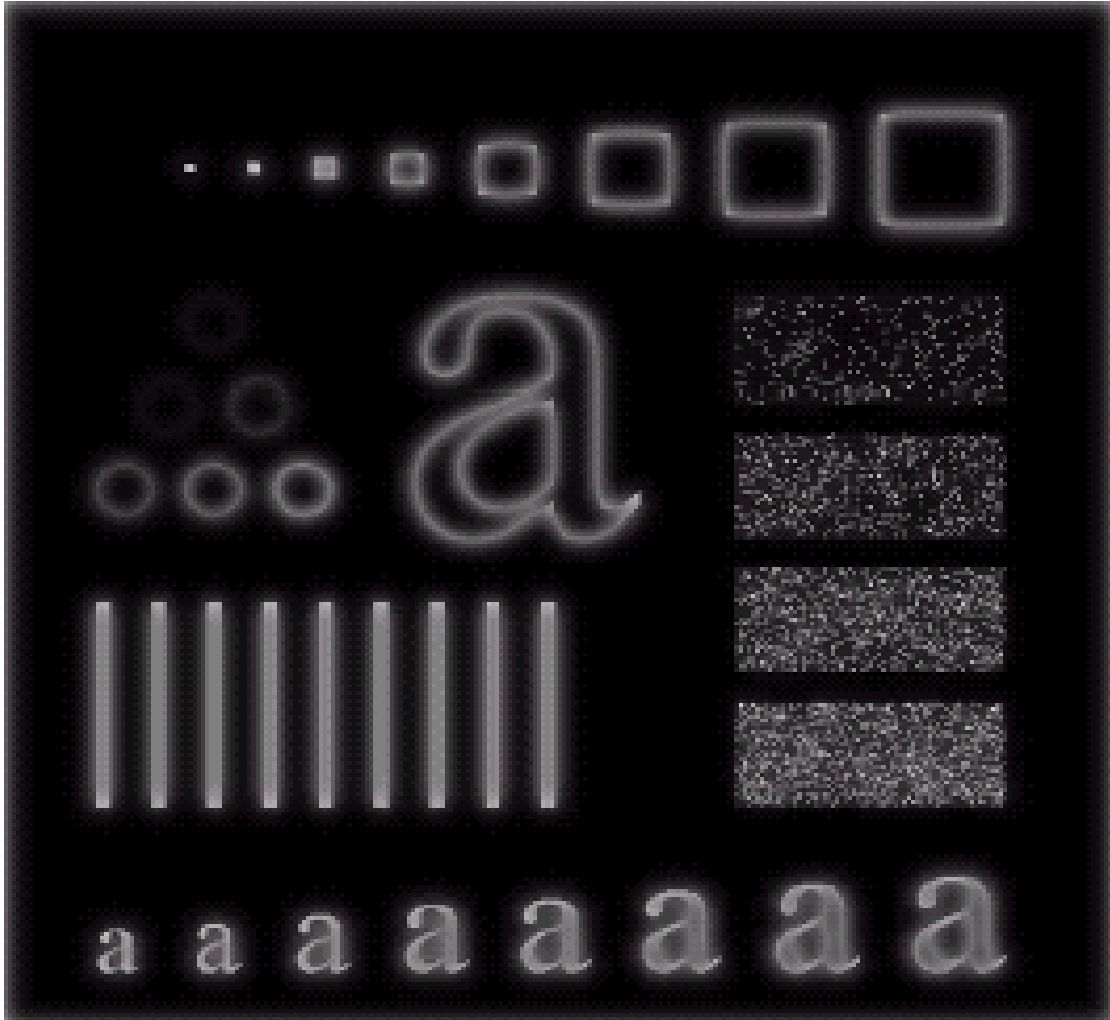
Results of ideal
high pass filtering
with $D_0 = 15$

Highpass Filter Comparison



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

Highpass Filter Comparison



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

Highpass Filtering Example

Original image



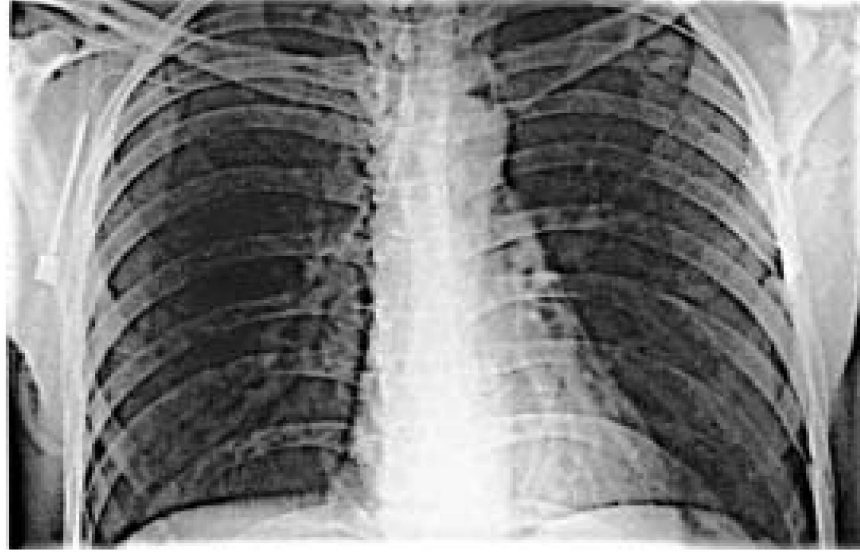
High frequency
emphasis result



Highpass filtering result

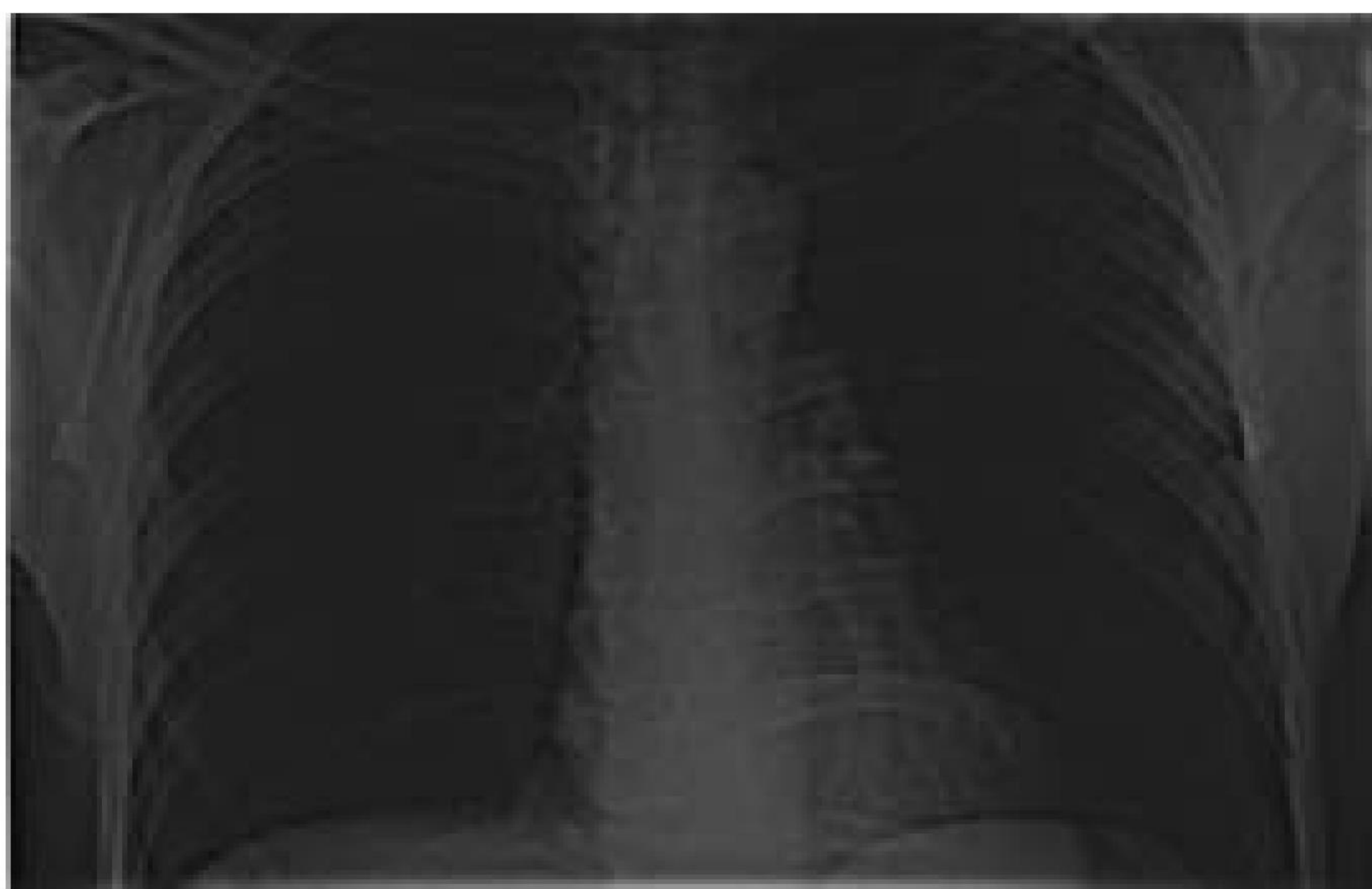


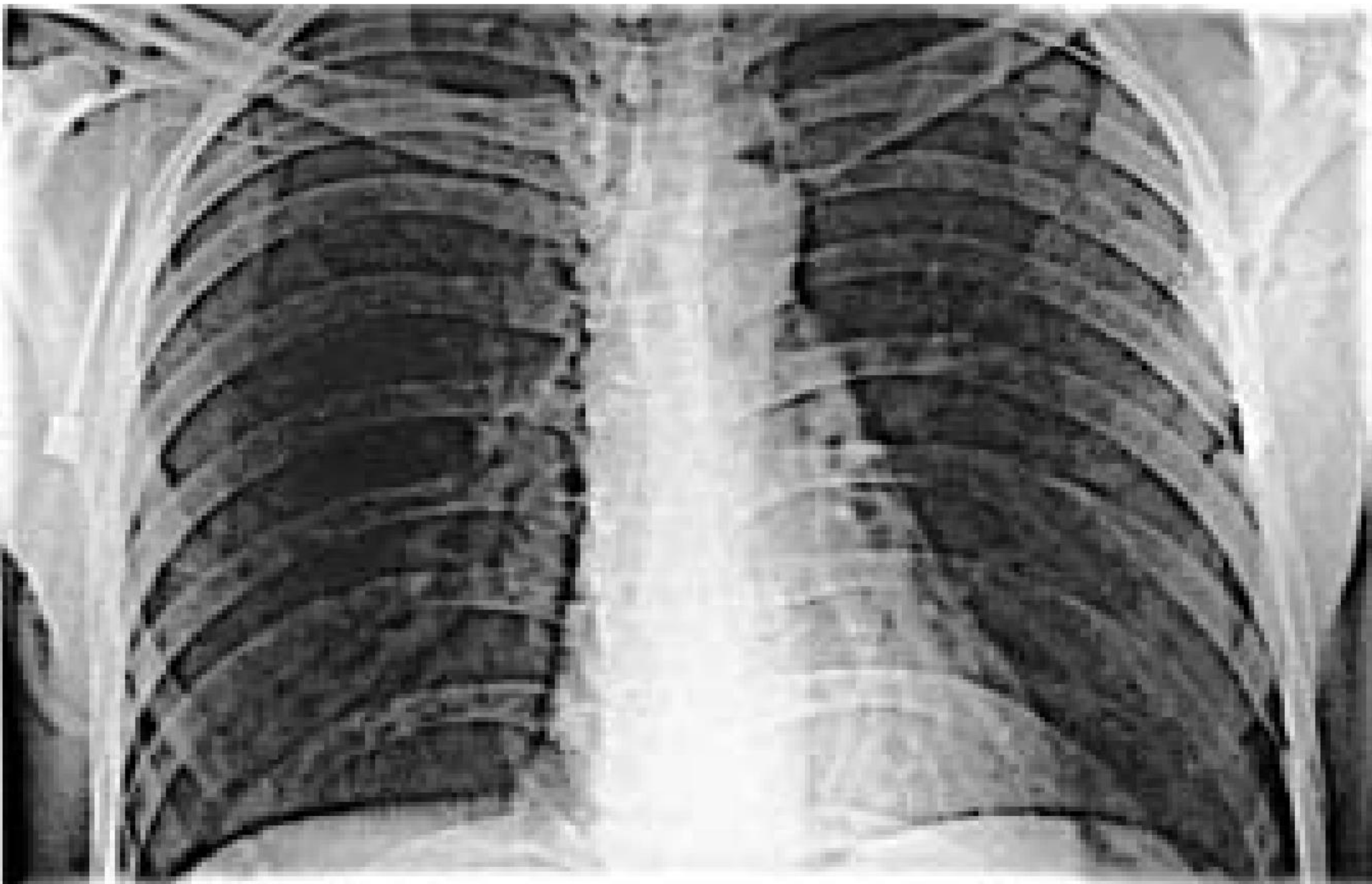
After histogram
equalisation









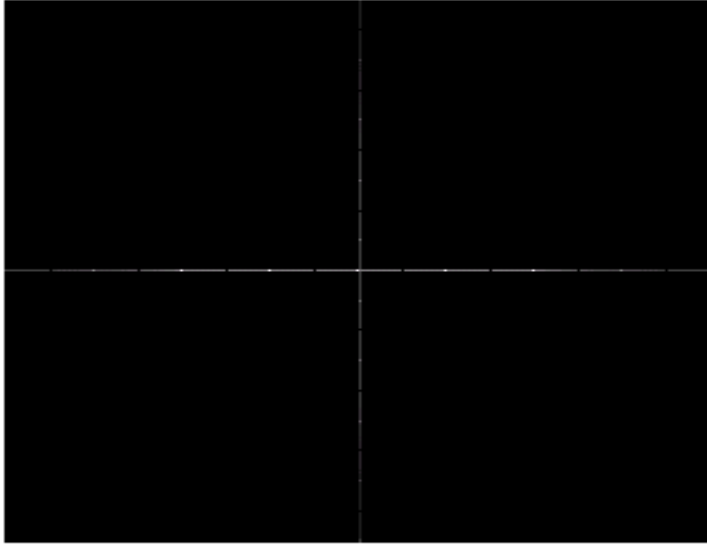


Laplacian In The Frequency Domain

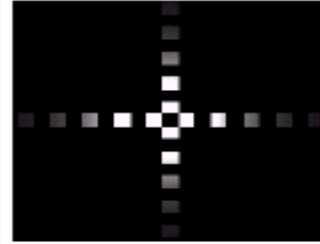
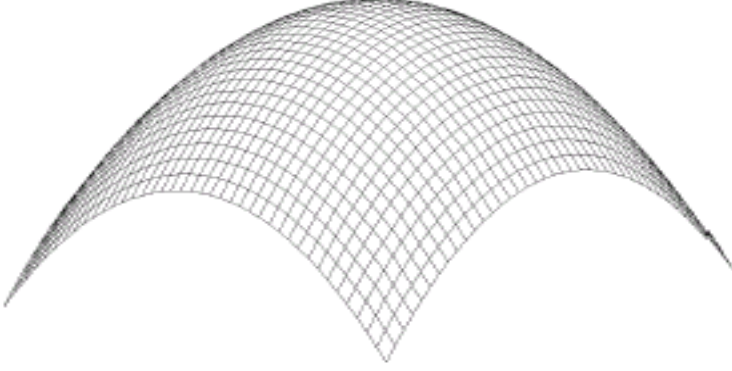
59
of
54

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

Inverse DFT of
Laplacian in the
frequency domain



Laplacian in the
frequency domain



| | | |
|---|----|---|
| 0 | 1 | 0 |
| 1 | -4 | 1 |
| 0 | 1 | 0 |

Zoomed section of
the image on the
left compared to
spatial filter



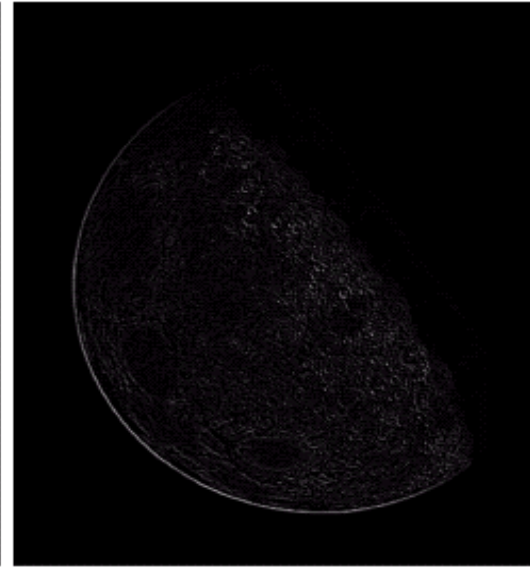
2-D image of Laplacian
in the frequency
domain

Frequency Domain Laplacian Example

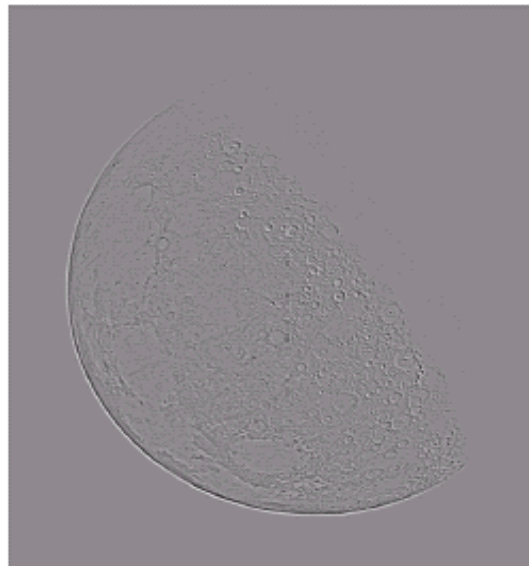
Original
image



Laplacian
filtered
image



Laplacian
image scaled



Enhanced
image



The reason that Fourier based techniques have become so popular is the development of the *Fast Fourier Transform (FFT)* algorithm

Allows the Fourier transform to be carried out in a reasonable amount of time

Reduces the amount of time required to perform a Fourier transform by a factor of 100 – 600 times!

Similar jobs can be done in the spatial and frequency domains

Filtering in the spatial domain can be easier to understand


Filtering in the frequency domain can be much faster – especially for large images

In this lecture we examined image enhancement in the frequency domain

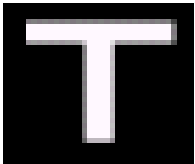
- The Fourier series & the Fourier transform
- Image Processing in the frequency domain
 - Image smoothing
 - Image sharpening
- Fast Fourier Transform

Next time we will begin to examine image restoration using the spatial and frequency based techniques we have been looking at

Interesting Application Of Frequency Domain Filtering



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Interesting Application Of Frequency Domain Filtering



