CSCI435 – Computer Vision

Lecture 4

Image Quality

Image Enhancement

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Machine Vision Concept (review)

- Machine Vision is a multistage process where each previous stage affects performance of all following stages

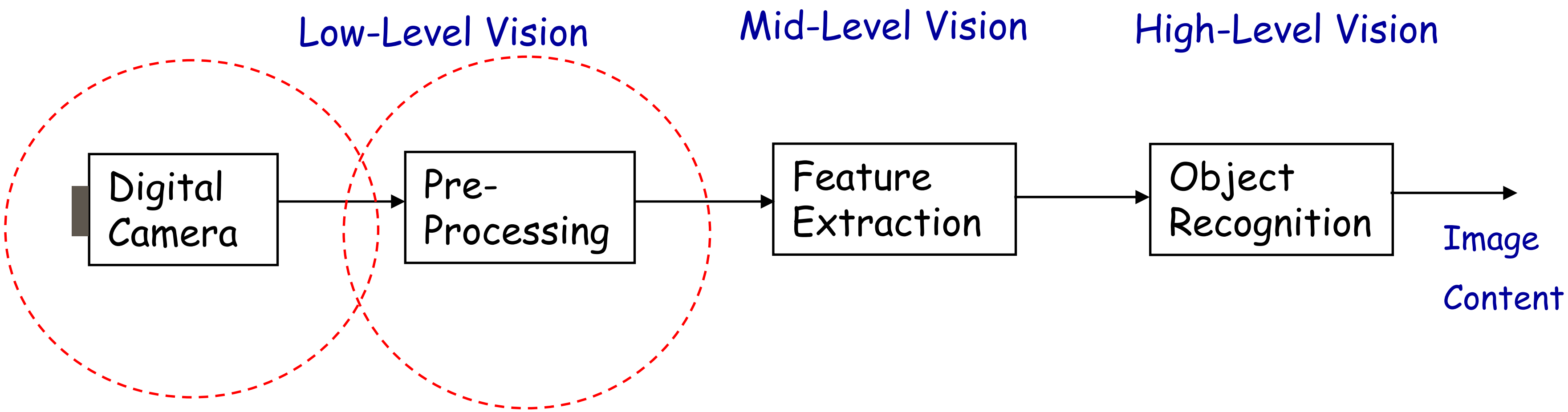


Image Enhancement

The objective of Image Enhancement is to produce an image that is more **suitable** than the original one

The word **suitable** has different meaning for different applications

Criteria of Quality

- Image capturing process inevitably introduces distortions that degrade image quality
- Visual quality assessment is not sufficient for computer vision applications
- Image quality should be based on quantitative characteristics which in the end affect object recognition and measurement of parameters
- All distortions should be divided into two categories:
  - those which can be corrected by digital enhancement
  - those which cannot be corrected by digital enhancement and require optimisation of the image capturing process

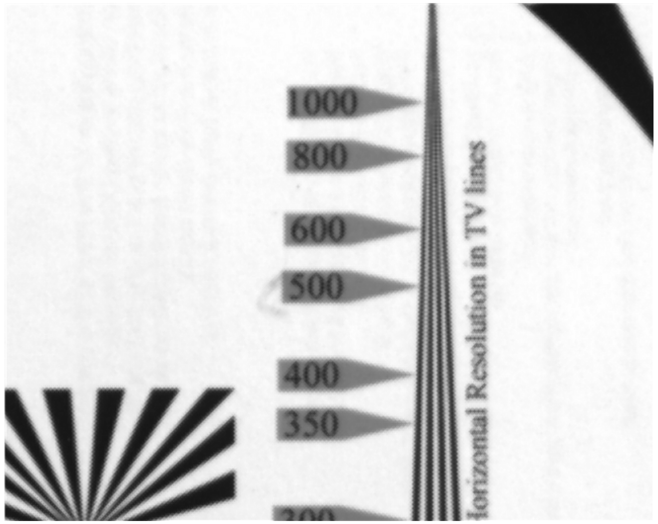
Sharpness

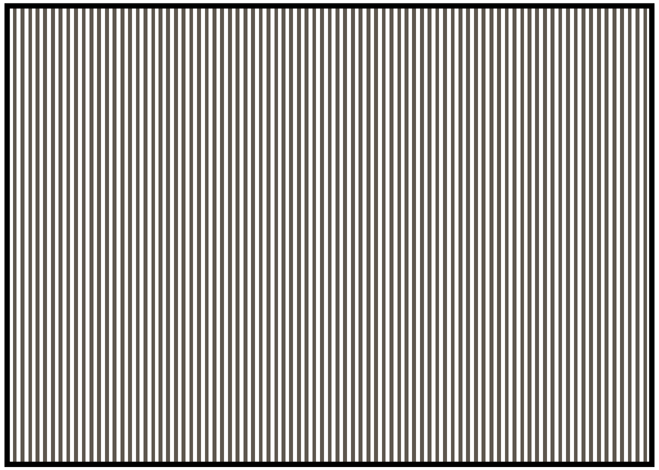
- Sharpness determine the amount of details that image can clearly reproduce
- Sharpness depends on several factors:

  - quality of the lens
  - focus accuracy
  - sensor resolution (sensor dimension in pix)
  - CFA interpolation algorithm
  - blur caused by camera movement (handshaking, motion blur, etc)
- Camera manufacturers are usually advertise only sensor resolution

Sharpness

- The measurable parameter of sharpness is how many black-white lines can be seen in vertical or horizontal direction





If a sensor size is 800x600 pix, how many black-white lines can be clearly counted at best?

Sharpness

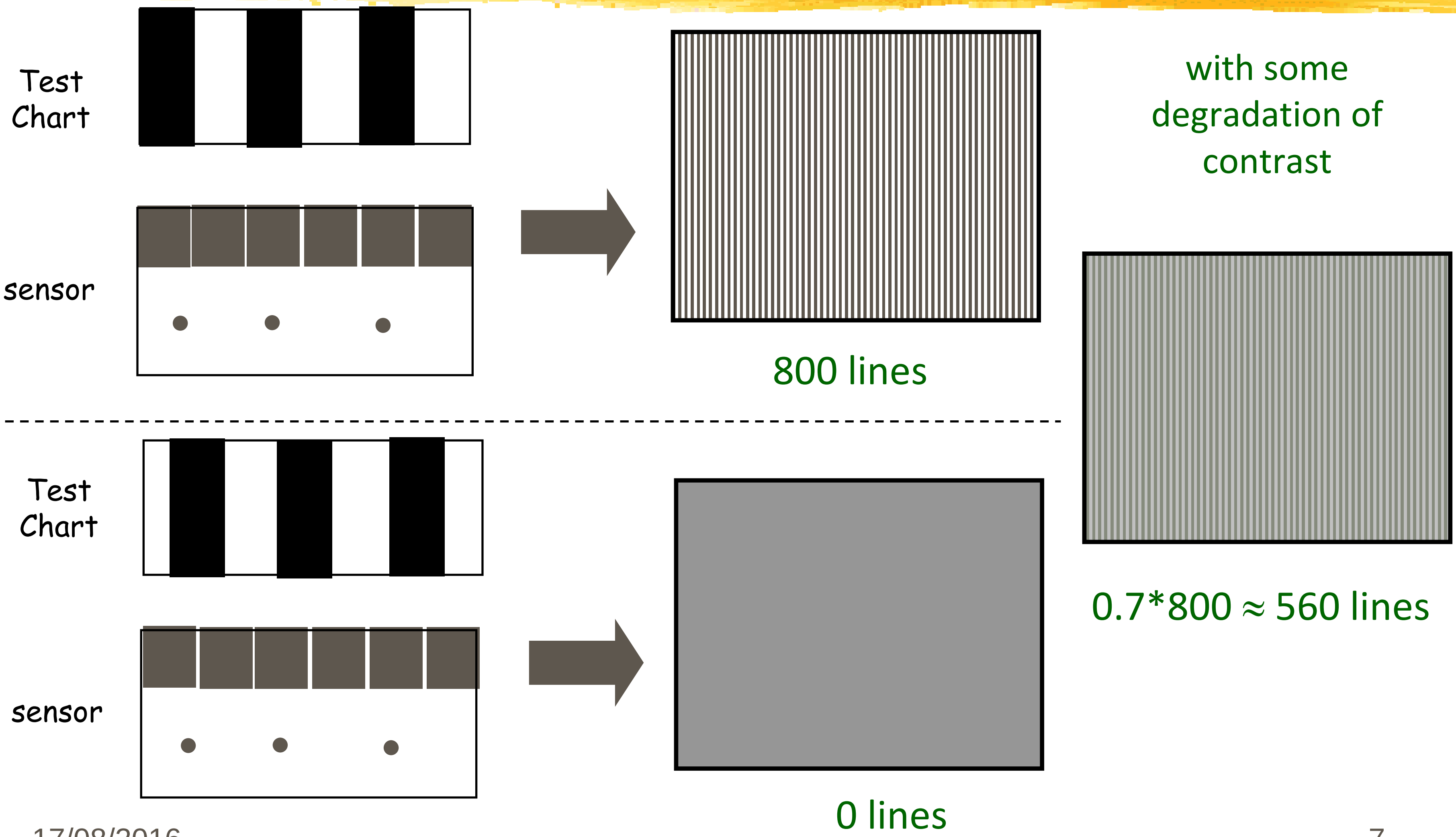

Test Chart
sensor
800 lines
with some degradation of contrast
Test Chart
sensor
0 lines
0.7*800 ≈ 560 lines

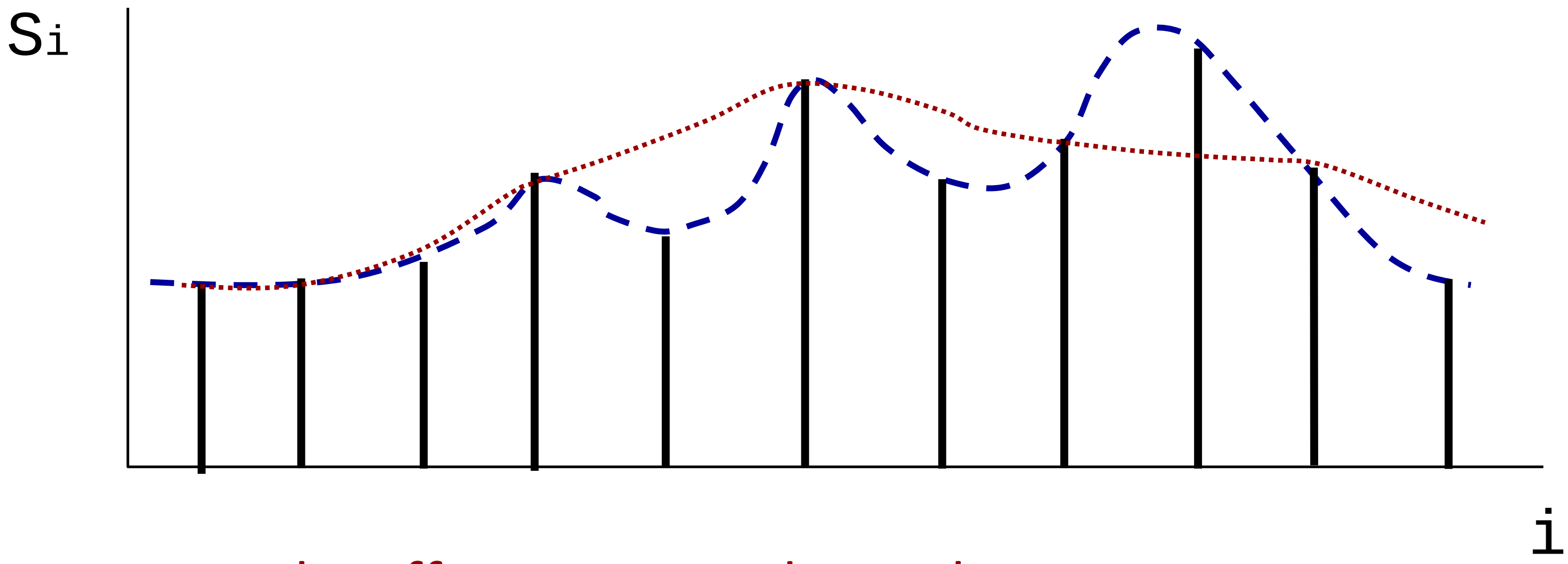
Image Rescaling (Resizing)

- Some image analysis and object recognition operations do not require high resolution images
- Image size can be reduced through sub-sampling

Can a half size image be produced simply by discarding every second sample?

Image Rescaling (Resizing)

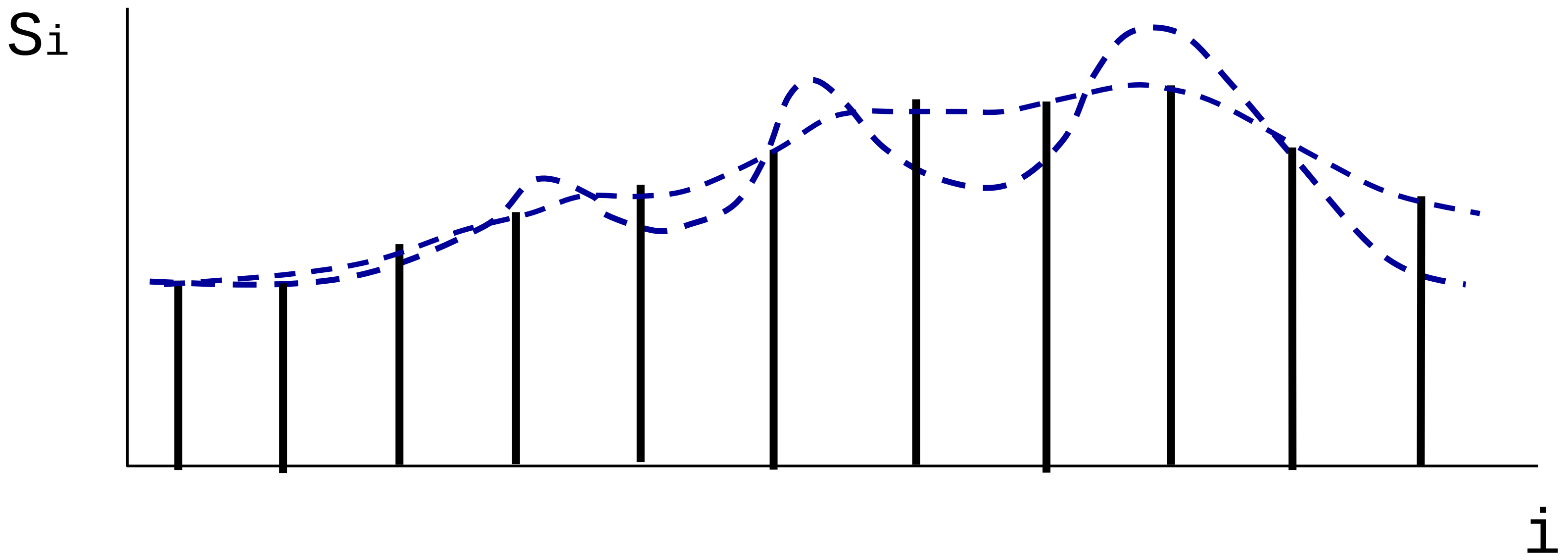
- Straightforward sub-sampling of an image will very likely violate requirements of the sampling theorem ($\Delta \leq 1/(2 * F_{max})$) introducing aliasing



take off every second sample

Image Rescaling (Resizing)

- To satisfy the sampling theorem requirements, F_{max} of a sequence must be reduced to $F_{max}/2$ before down sampling



If $F_{max} = F_{max}/2$, down-sampling does not cause aliasing

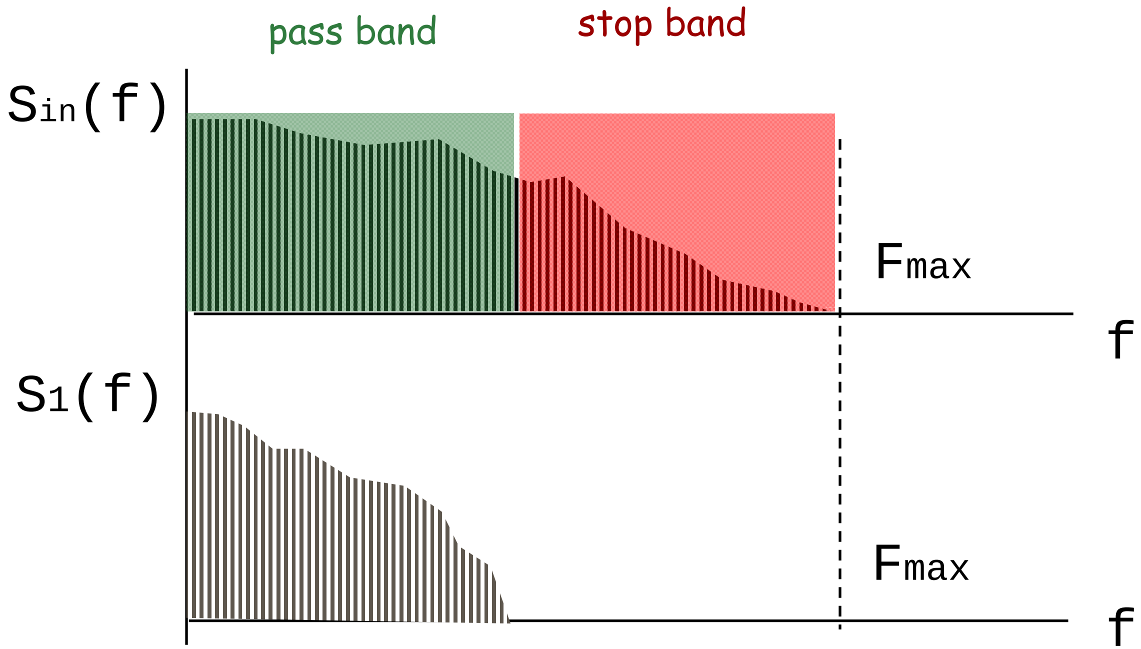
Image Rescaling (Resizing)

- Image rescaling by factor of N is a two-stage process

  1. Limit the maximum frequency to F_{max}/N using an appropriate band limiting filter

  2. Decimate image by leaving only one sample out of N

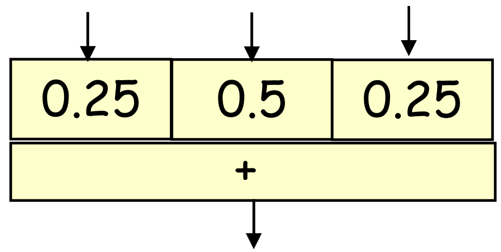
Example: N = 2

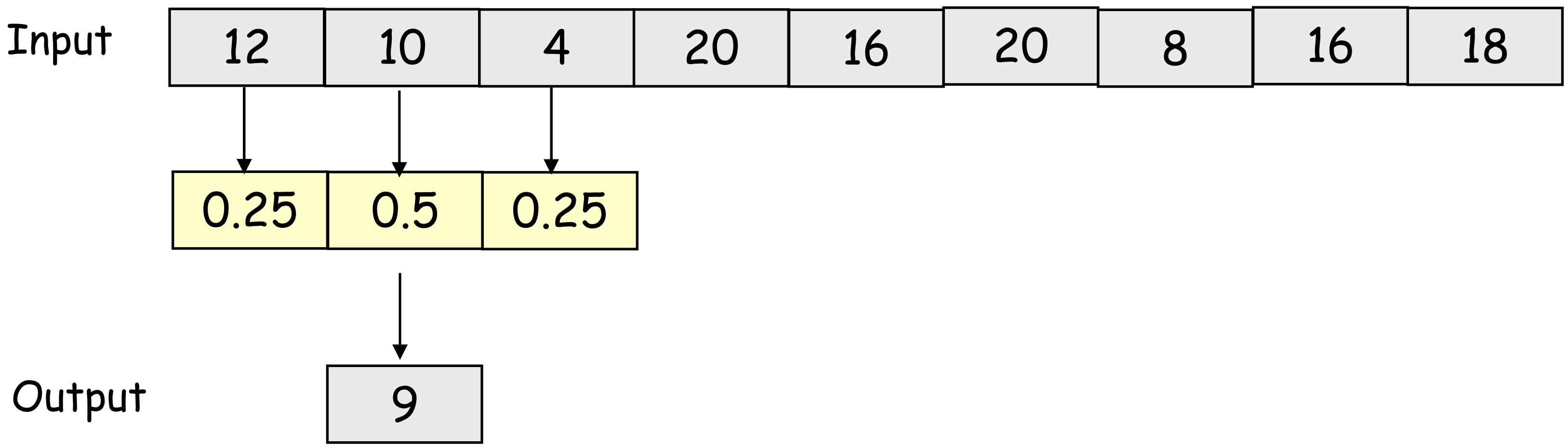


Band Limited Low-Pass Filter

- Band Limited filters are usually implemented as a linear operation that uses a weighted sum of input samples to produce an output sample

Example: A Low Pass Filter with three weights





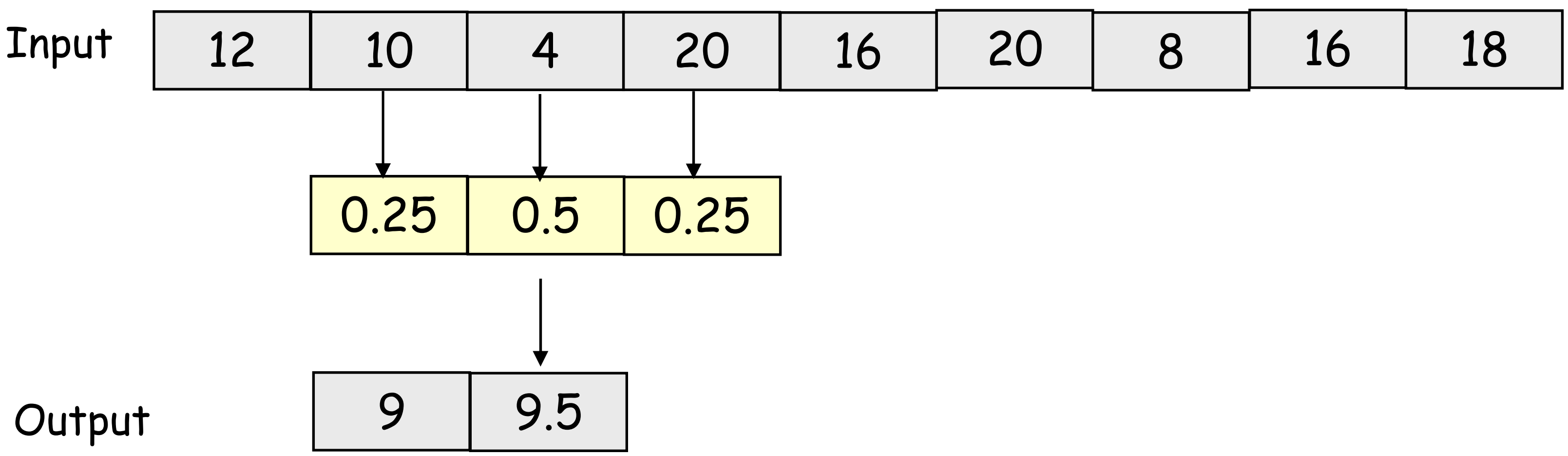
12*0.25 + 10*0.5 + 4*0.25 =9

Band Limited Low-Pass Filter

- Band Limited filters are usually implemented as a linear operation that uses a weighted sum of input samples to produce an output sample

Example: A Low Pass Filter with three weights

0.25	0.5	0.25



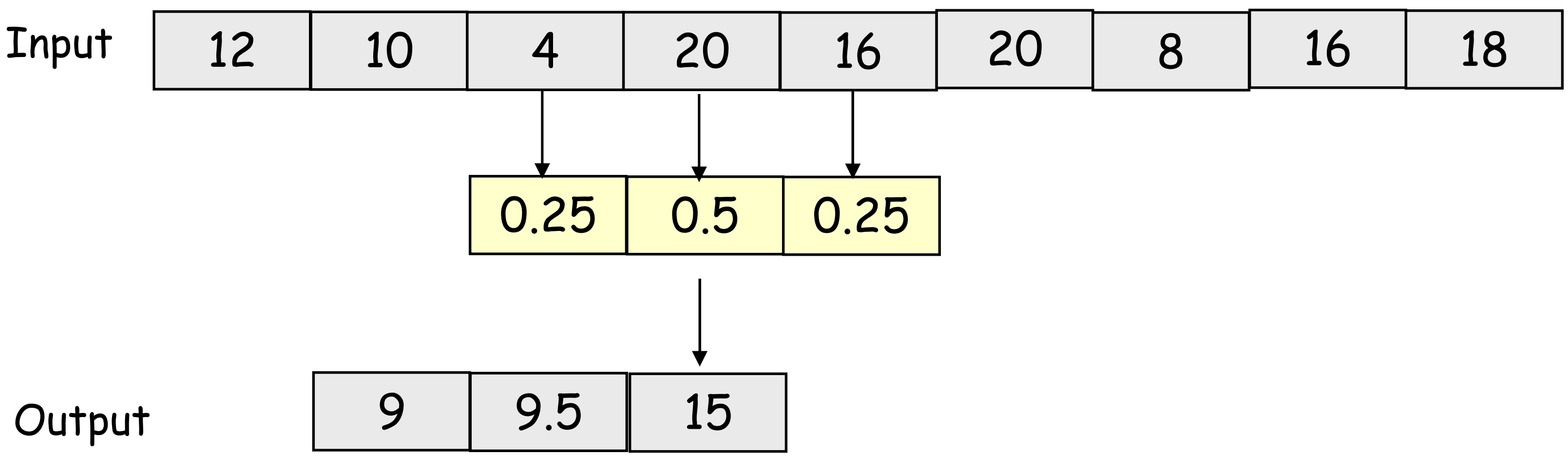
10*0.25 + 4*0.5 + 20*0.25 =9.5

Band Limited Low-Pass Filter

- Band Limited filters are usually implemented as a linear operation that uses a weighted sum of input samples to produce an output sample

Example: A Low Pass Filter with three weights

0.25	0.5	0.25

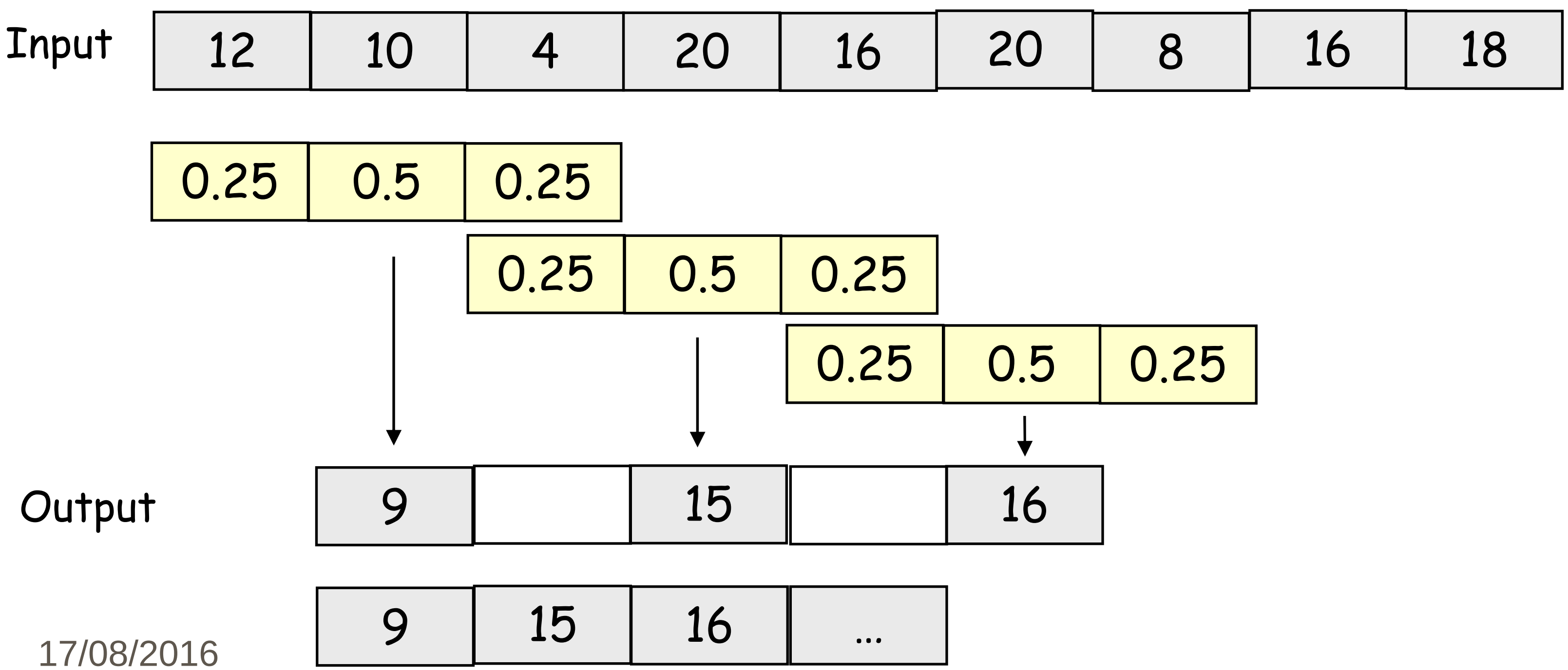


4*0.25 + 20*0.5 + 16*0.25 =15

Low-Pass Filter + Down-Sampling

- As some samples are to be discarded at the Stage 2, filtering and down-sampling processes can be combined to skip unneeded positions

Example: A Low Pass Filter and Down-sampling /2



Convolution

- The process of filtering is mathematically described as a convolution of two sequences
  1. x(n) - an input sequence
  2. h(n) - a sequence of filter weights
- The output sequence y(n)

$$y(n) = x(k) \otimes h(k) = \sum_{k} x(k) * h(n-k)$$

Example: h(-1) = 0.25 h(0) = 0.5 h(1)=0.25, other h(n) = 0

x(n) = { 12, 10, 4, 20, 16, 20, … }

$y(1) = x(0)*h(1) + x(1)*h(0) + x(2)*h(-1) \cancel{+ \ldots} = 3+5+1 = 9$

$y(2) = \cancel{x(0)*h(2)} + x(1)*h(1) + \ldots$

$y(3) =$

2D Low-Pass Filter

- As images are 2D arrays of samples, they are filtered by 2D filters
- A 2D filter is a 2D array of weights (filter coefficients)

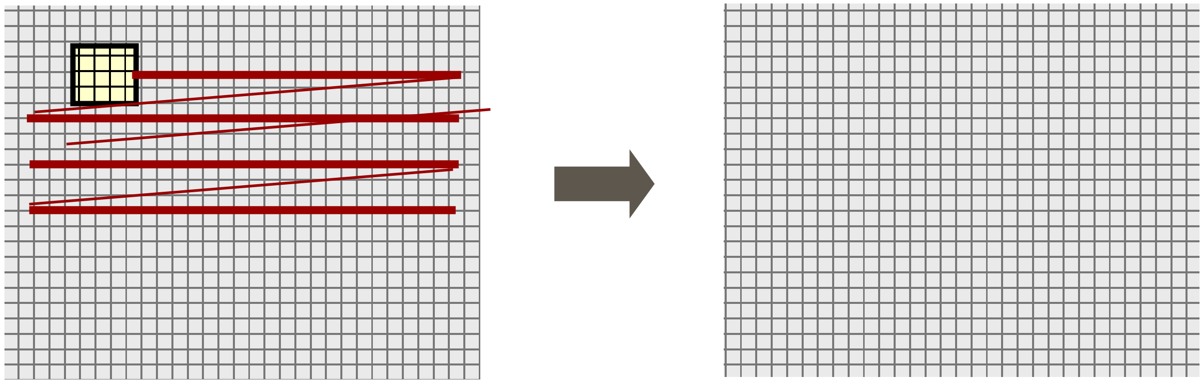
Example: h(n, m) =

0.11	0.11	0.11
0.11	0.11	0.11
0.11	0.11	0.11

To get one filtered pixel:

- 9 multiplications
- 6 additions

- A 2D filter moves across an image column-by-column, row-by-row to produce a processed output image



2D Low-Pass Filter

Example:

0.11	0.11	0.11	0.11	0.11	0.11
0.11	0.11	0.11	0.11	0.11	0.11
0.11	0.11	0.11	0.11	0.11	0.11
0.11	0.11	0.11	0.11	48	46
52	47	45	52	47	45
54	57	50	54	57	50

1. Multiply filter coefficients with the corresponding pixel samples and add the results together to produce a filtered sample
2. Place the filtered sample in the output image at the position corresponding to the current position of the filter centre
3. Move the filter to the next position

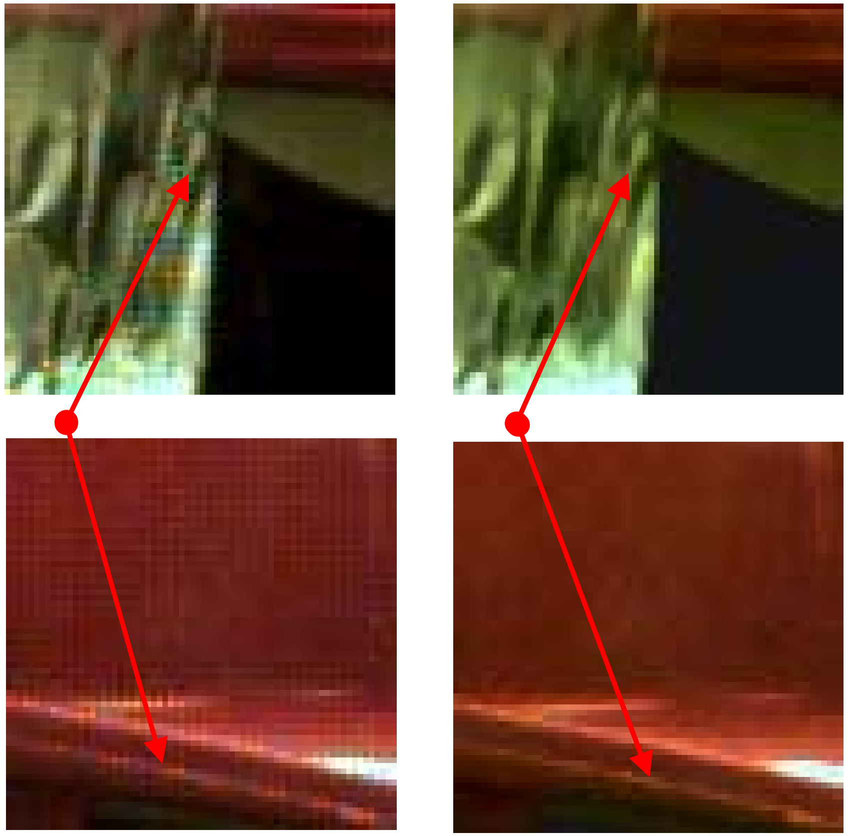
Example

Example

Down-sampled image

Colour Aliasing

- RGB components of image sensors with Bayer pattern are sampled at different rates. Which rate must be matched by lens sharpness?
- Camera manufacturers usually match the G rate even though this results in aliasing for R and B
- Aliasing cannot be removed, but its visibility can be reduced by CFA Interpolation

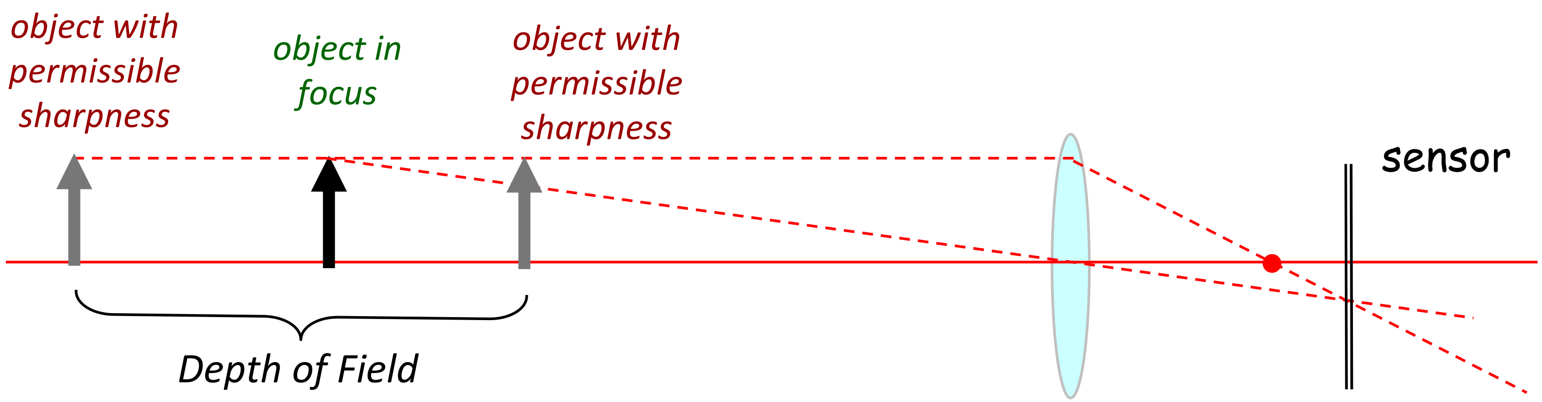


Focusing

- When a lens is focused on an object, theoretically, all objects at other distances S from the camera are out of focus

  `1/S + 1/s = 1/f`

- Practically, objects slightly in front and behind the object are also appear reasonably sharp. This extra depth is called Depth of Field

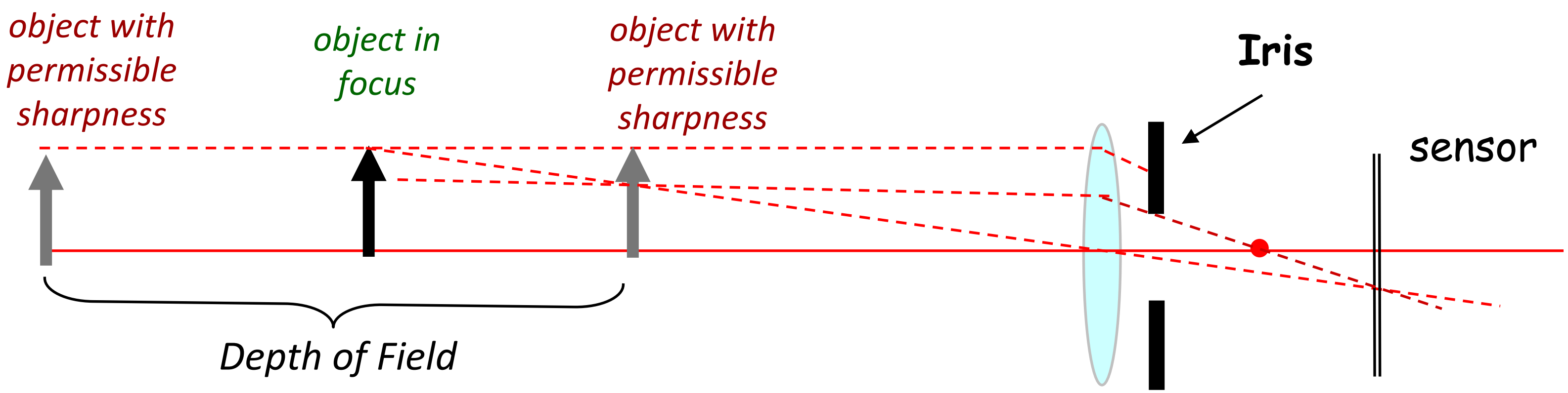


- All objects beyond the depth of field are blurred

Focusing

- Small depth of field is usually a desirable feature of art photos to emphasise an object of interest and isolate it from the background
- Computer Vision Cameras may require a wide depth of field to facilitate analysis of complex scenes
- The greater F, the greater depth of field

  $F = f/D$, where D can be adjusted by changing Iris



What is a side effect of increasing F?

Out-of-Focus Blur

- Leads to losses in resolution for all objects which are outside the depth of field

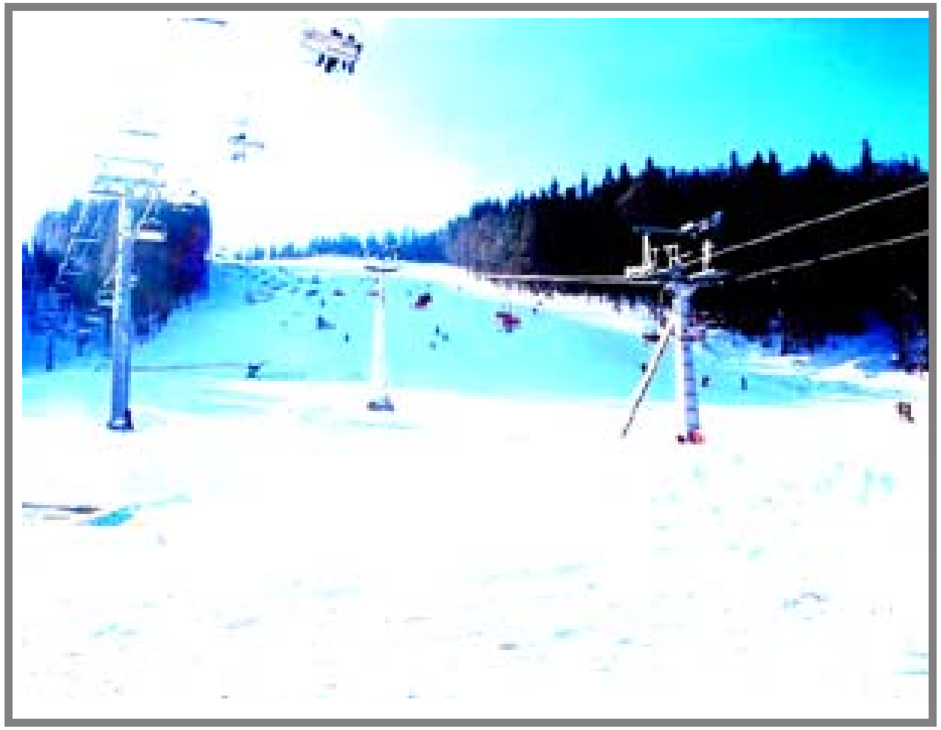
- Out-of-Focus Blur affects images in a way similar to low-pass filtering
- Digital image processing can improve image sharpness by applying inverse filters, but as a side effect it introduces ringing artifacts

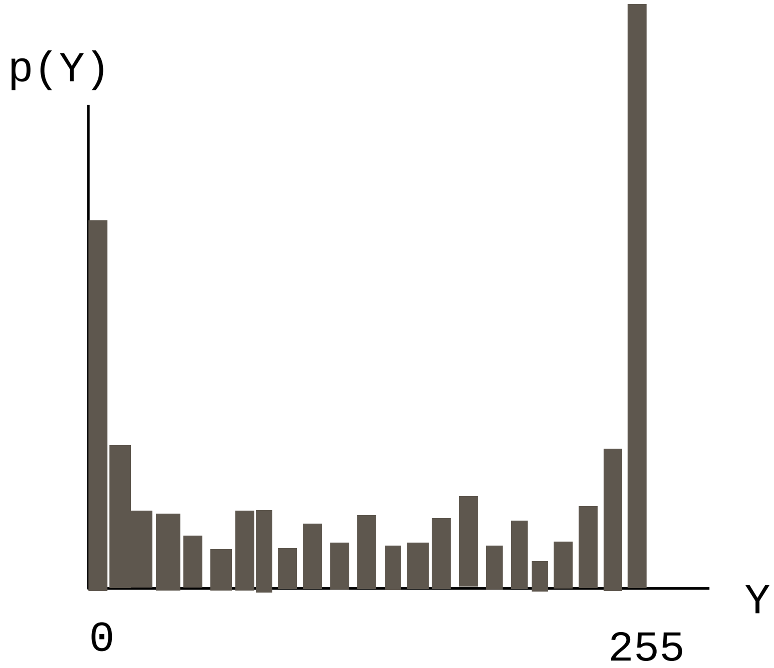
Motion Blur

- Leads to losses in resolution in the directions of fast motion

- Digital image processing can improve image sharpness, but as a side effect it introduces ringing artifacts

Saturation

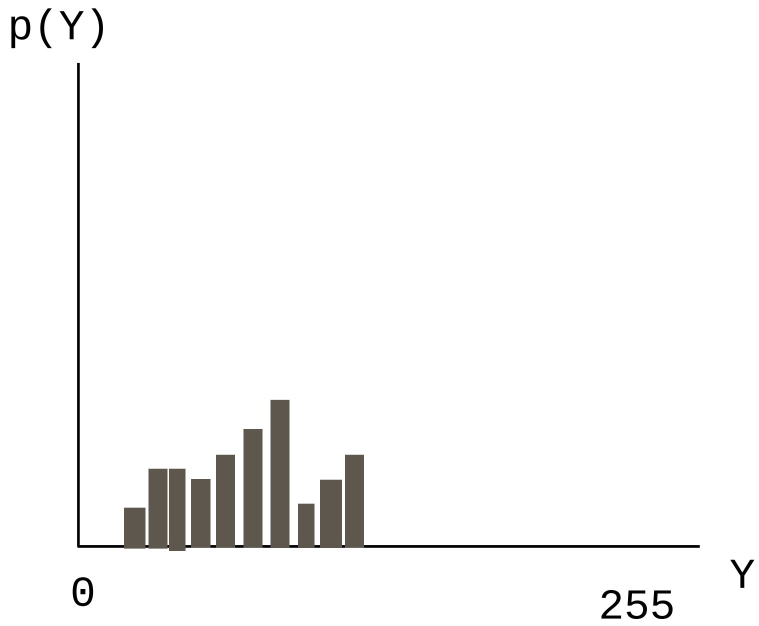




- Capturing of high dynamic range scenes may cause saturation

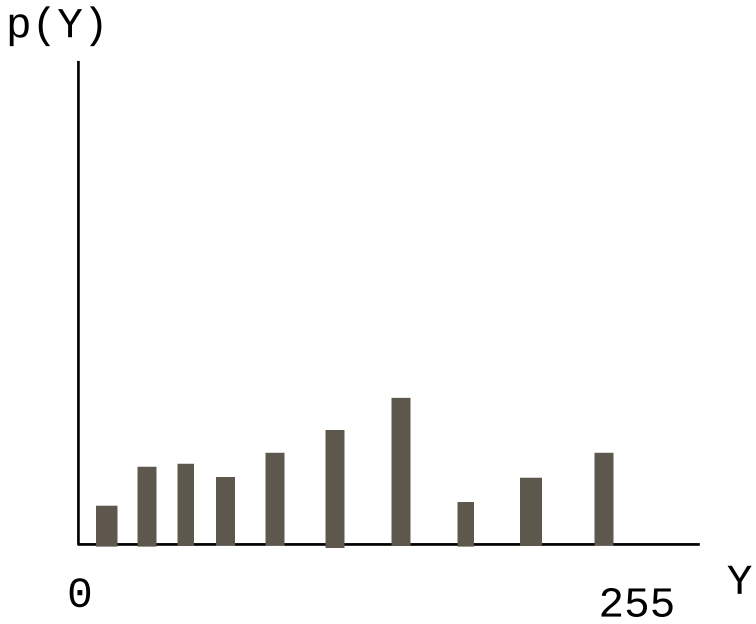
- Reaching maximum quantisation level 255 samples are clipped producing uniform areas with all details lost

Under-Exposure



- Digital cameras with inefficient Auto-Exposure and Automatic Gain Control may capture images which do not utilise all quantisation levels leading to loss of details

Under-Exposure: contrast enhancement

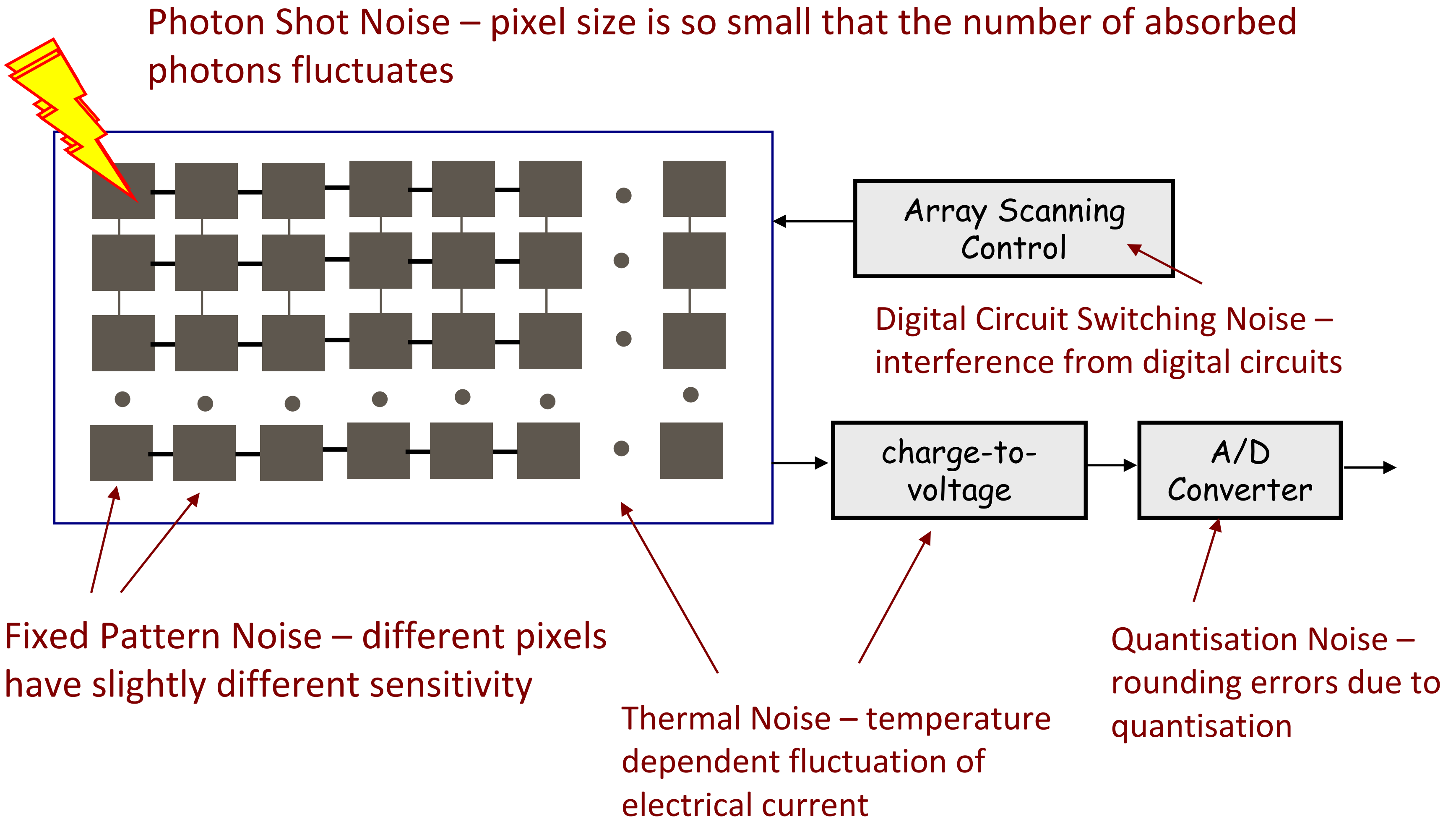


- Simple contrast enhancement changes only visual appearance of the image while the same number of quantisation levels is used

Noise

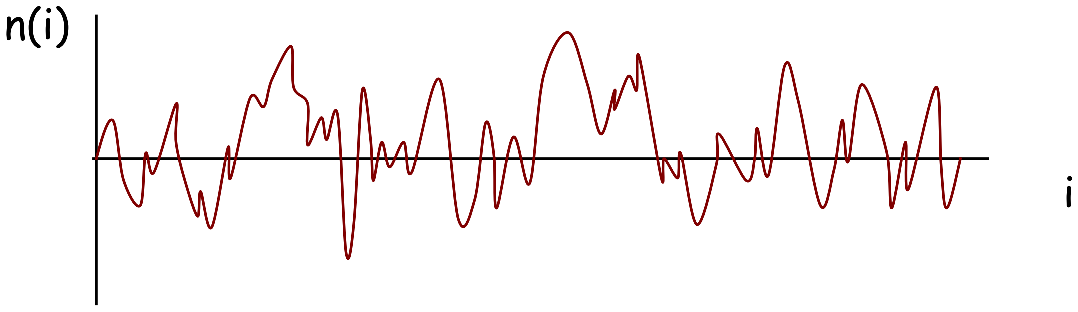
- Digital camera is an electronic device that besides digital, contains analog components
- Receiving and processing target signals they are affected by random fluctuation of electric current, random variation of electronic circuit parameters and interferences from other electronic components
- Noise is a random process and thus it cannot be eliminated in a similar way to other factors affecting image quality such as: resolution, defocus, colour fidelity, under-exposure, etc
- It is not possible to reduce noise without employing statistics and the theory of probability

Sources of Noise

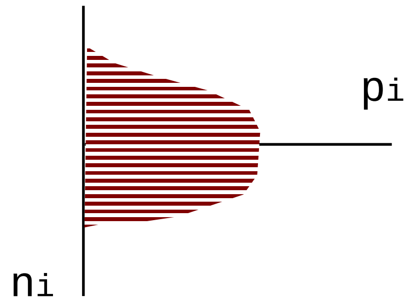


Parameters of Noise

- Noise is a random process and thus, it can be described only statistically



Probability Density



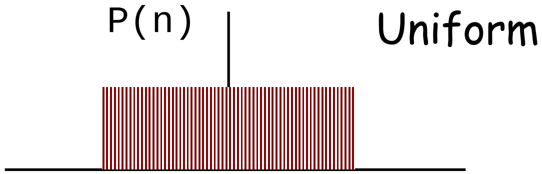
- Other statistical parameter also characterise noise

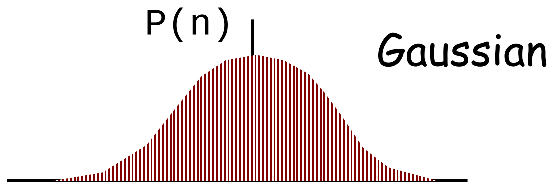
The mean: $\bar{n} = \frac{1}{n} * \Sigma n_i$ or $\bar{n} = \Sigma p_i * n_i$

The standard deviation: $\sigma = \sqrt{\frac{1}{n} * \Sigma (n_i - \bar{n})^2}$ or $\sigma = \Sigma p_i * (n_i - \bar{n})^2$

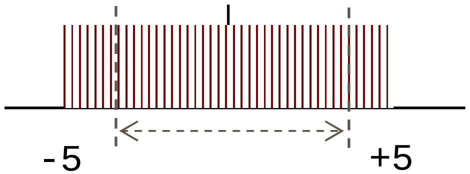
Noise Probability Density

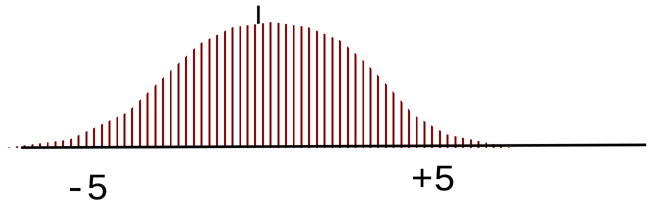
- Different types of noise have different probability densities
- There are two the most common Probability Densities





Q: A uniform area of a digital image with luminance Y = 200 is affected by noise. What is the probability that a luminance sample affected by noise is visually different from the uniform background? Consider the uniform and the Gaussian distributions.

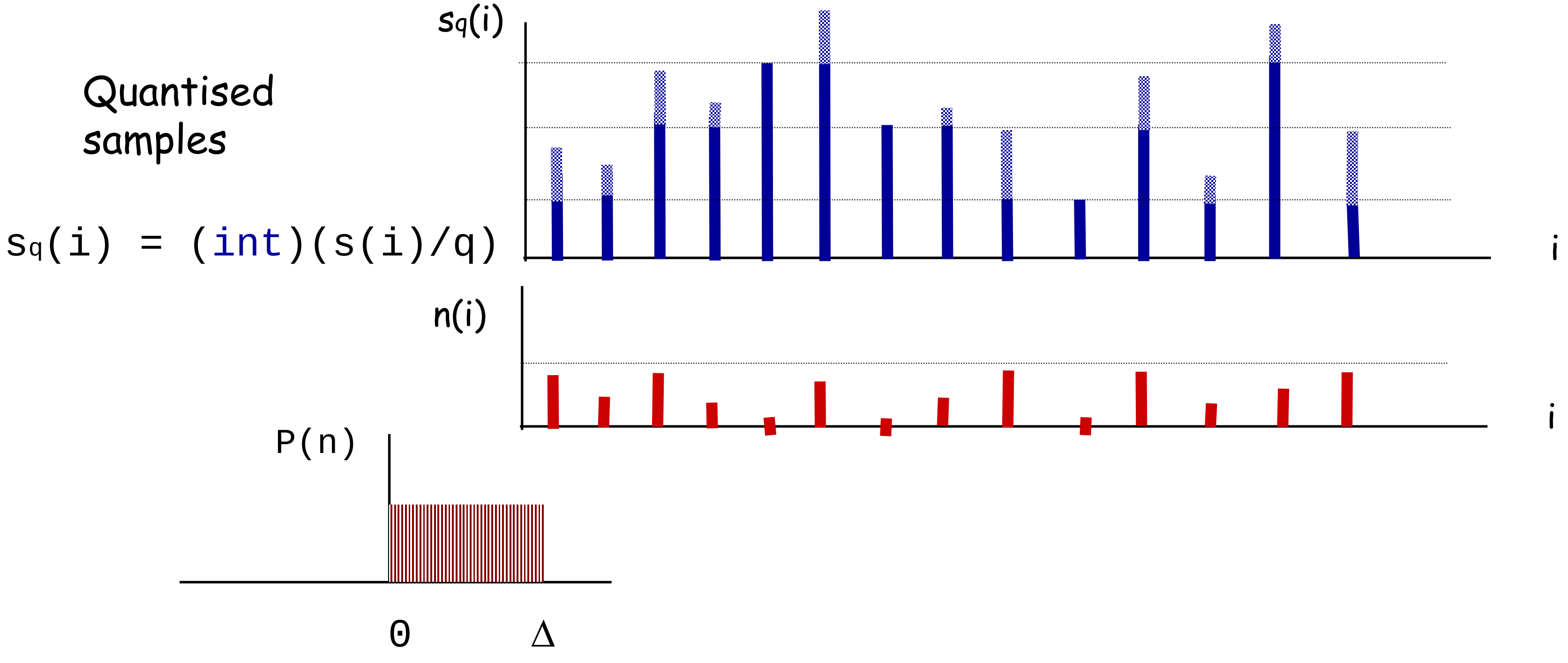




According to Webber's law the visibility threshold is 2%. 2% of 200 is ±4

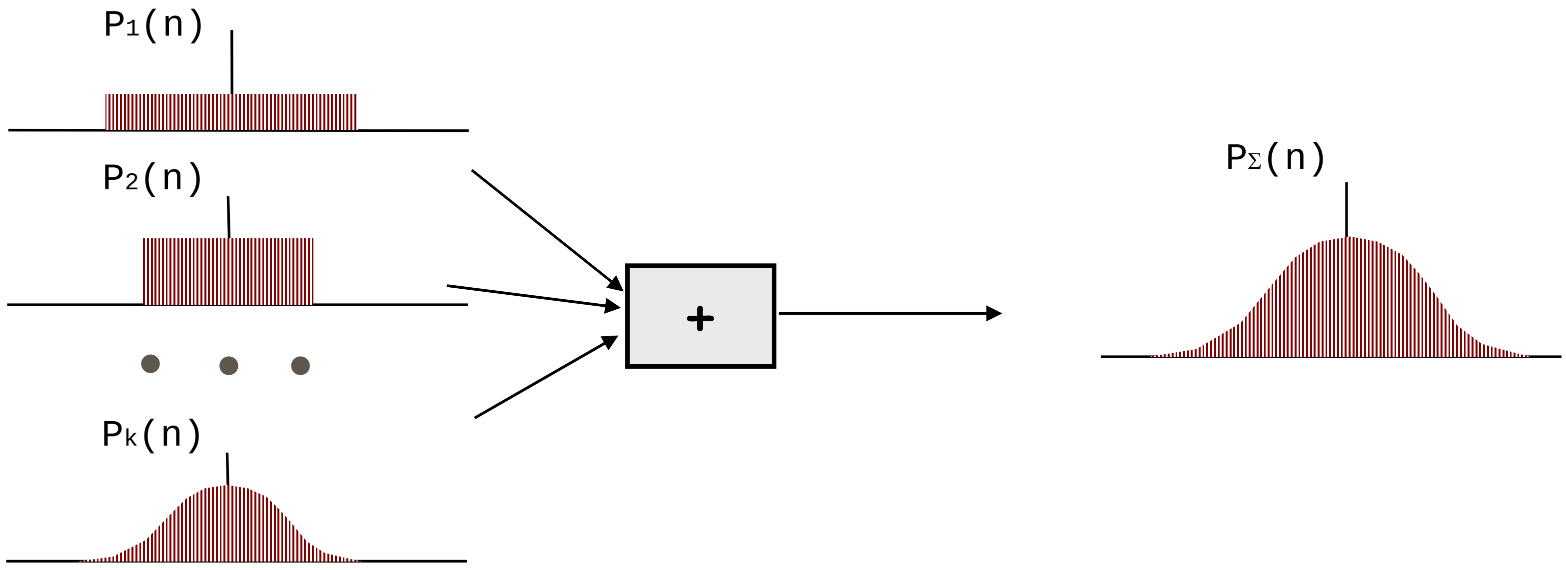
Uniform: P(|n|>4) = 20%

Quantisation Noise



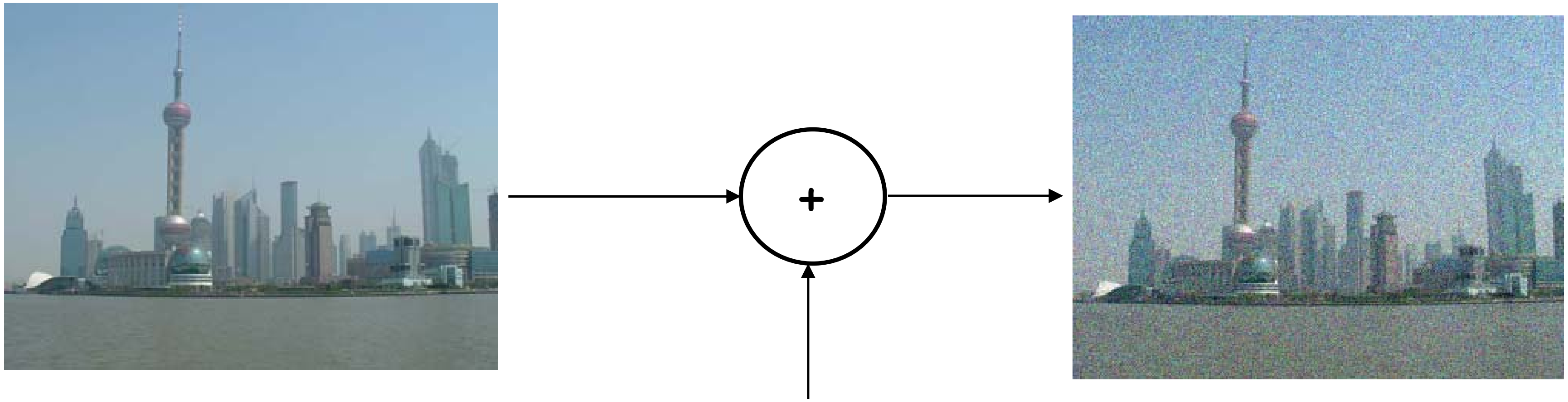
- Quantisation noise has a uniform probability density in the range [0… Δ] , or [- Δ/2 ... Δ/2] if rounding used instead of truncation

Central Limit Theorem



- The sum of a large number of independent random processes will have approximately Gaussian probability density
- As image noise comes from several independent sources its distribution is approximately Gaussian with $\bar{n} = 0$

Noise Model



An ideal noise free image

`n(i, j)`
Gaussian noise

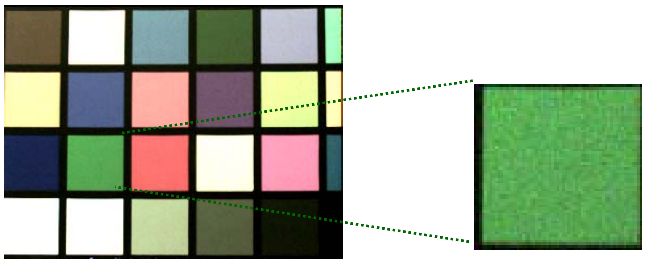
A real image

- Image quality analysis, image processing and image enhancement algorithms are based on the model that noise is additive to image samples with 0-mean Gaussian distribution

Quiz

- Images of Macbeth Colour Checker are used for measuring colour fidelity of the colour correction. The images are affected by noise with the standard deviation above the visibility threshold. Each colour patch is 50x50 pix. Gamma correction is disabled.

Can the noise affect the measurements?



→ R, G, B

$$G + \cancel{\bar{n}} = G$$

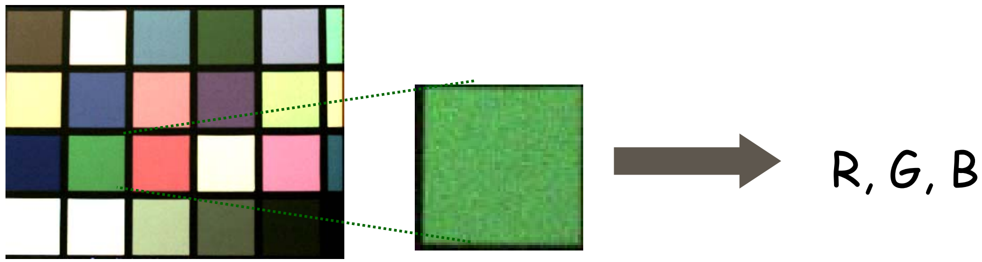
- For green plane:

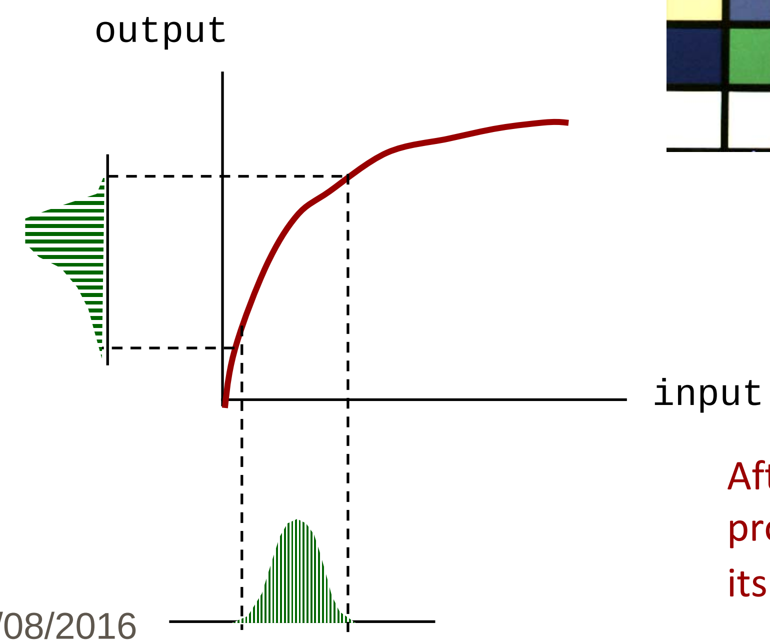
$$G_n = \frac{1}{2500}\sum_{50}\sum_{50} S_n(i,j) = \frac{1}{2500}\sum_{50}\sum_{50}(S(i,j)+n(i,j)) = G + \frac{1}{2500}\sum_{50}\sum_{50} n(i,j)$$

Quiz

- Images of Macbeth Colour Checker are used for measuring colour fidelity of the image processing chain that included Gamma Correction. The images are affected by noise with the standard deviation above the visibility threshold. Each colour patch is 50x50 pix.

Can the noise affect the measurements?

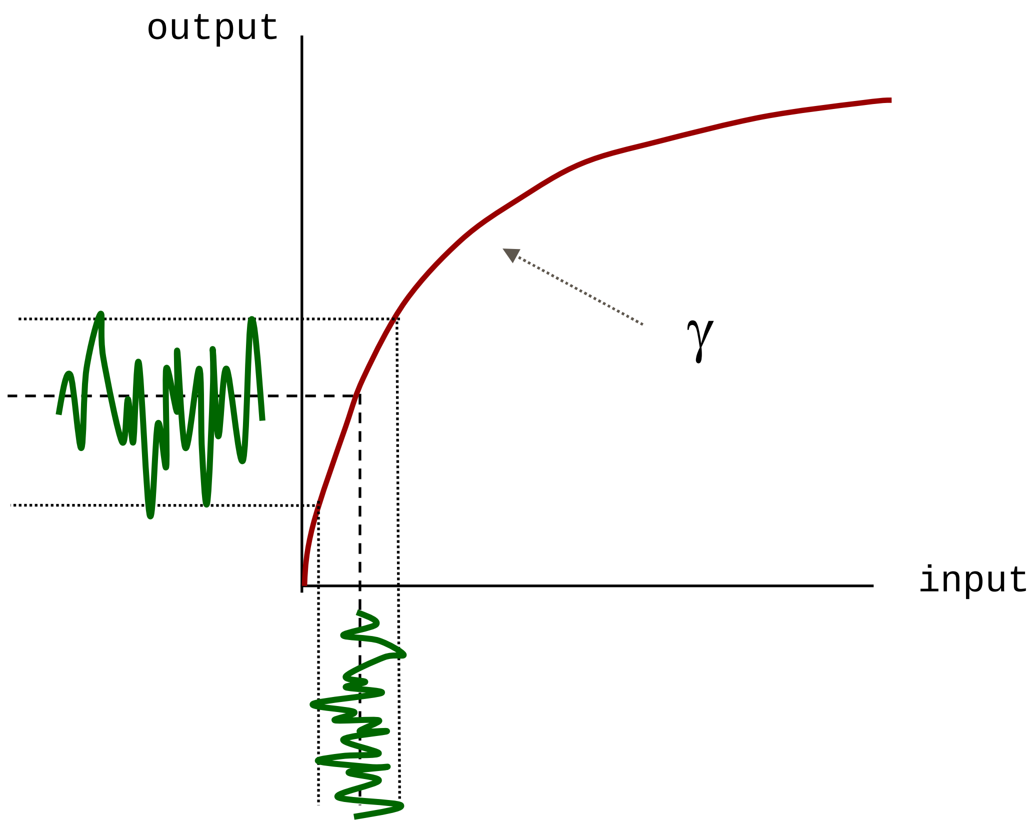


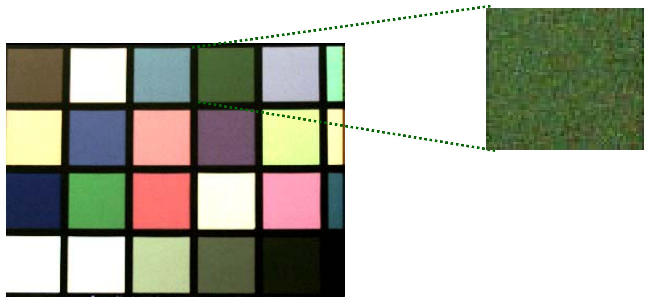


After the Gamma Correction stage, noise probability density is not symmetrical and its mean is not equal to 0. Thus, $G_n \neq G$

Gamma Correction and Noise

- Non-linearity of Gamma Correction leads to noise amplification in image regions with low illuminance





Colour Correction and Noise

- Improving accuracy of colour reproduction Colour Correction amplifies noise

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} 1.28 & -0.11 & -0.12 \\ -0.12 & 1.41 & -0.13 \\ -0.14 & -0.15 & 1.36 \end{bmatrix} * \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- As Colour Correction **T** is a linear operation and noise **n** is additive, we can analyse noise propagation independently

$\mathbf{I' = T*(I + n) = T*I + T*n}$, where $\mathbf{n}$ – noise vector

$$\begin{bmatrix} n_r' \\ n_g' \\ n_b' \end{bmatrix} = \begin{bmatrix} 1.28 & -0.11 & -0.12 \\ -0.12 & 1.41 & -0.13 \\ -0.14 & -0.15 & 1.36 \end{bmatrix} * \begin{bmatrix} n_r \\ n_g \\ n_b \end{bmatrix}$$

Colour Correction and Noise

- To simplify analysis, we make two assumptions:
  1. Noise in three colour channels R, G, B is statistically independent
  (explain why this is not strictly correct for cameras with Bayer pattern sensors)
  2. Noise standard deviation σ in R, G, B channels is the same
  (explain why this is not strictly correct for cameras with Bayer pattern sensors)

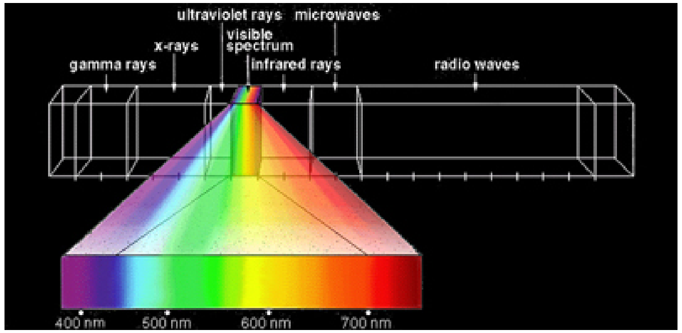
$$\sigma(n_g') = \sqrt{(0.12*\sigma(n))^2 + (1.41*\sigma(n))^2 + (0.13*\sigma(n))^2}$$

$\sigma(n_g') = 1.42*\sigma(n)$ noise deviation is 42% higher

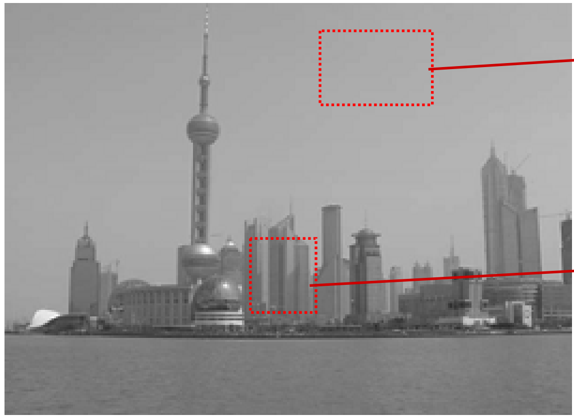
Exercise: What is the noise amplification in other colour channels?
Which colour channel noise is more visually noticeable?

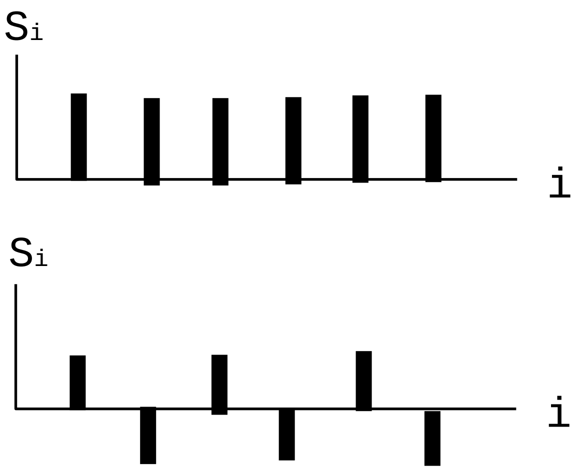
Image and Noise Spectral Properties

- Digital Image Spectrum should not be confused with the spatial spectrum of visible light



Electromagnetic spectrum of light
$\approx 400\text{nm} - 700\text{nm}$





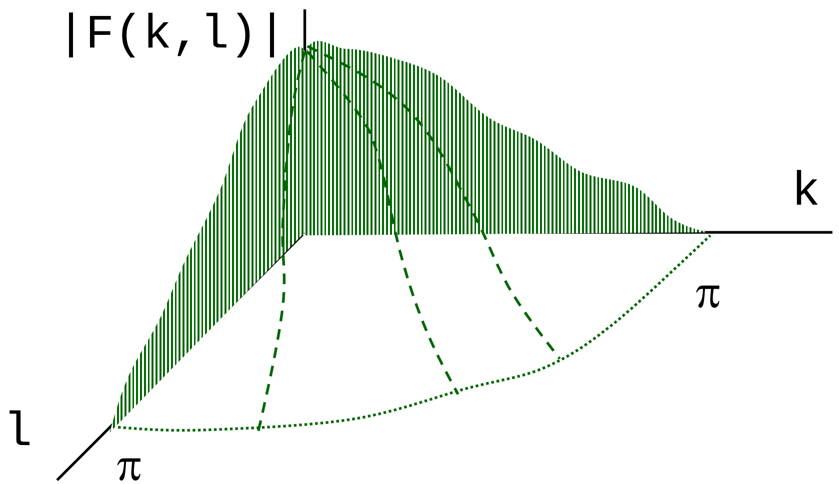
$f = 0$

$f = \pi$

Components of image spatial spectrum range from 0 to π

Image and Noise Spectral Properties

- Spatial Spectrum of Digital Images `F(k, l)` results from harmonic approximation of 2D sequences of image samples
- Spatial Spectrum of Digital Images is 2D (horizontal – vertical)
- Dominant components of natural images have smooth variation of luminance and colour, thus low spatial frequencies
- A typical spectrum of natural images



- The dominant frequencies are usually low
- High frequencies are usually not very powerful

Exercise: How would you explain the fact that diagonal spectrum components are usually weaker than horizontal and vertical once?

Image and Noise Spectral Properties

- Spatial spectrum of image white noise is 2D (horizontal – vertical)
- Spectrum is uniform

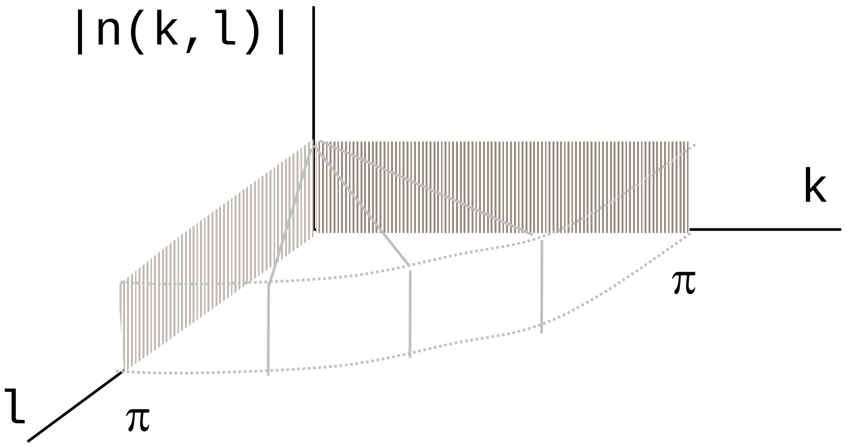


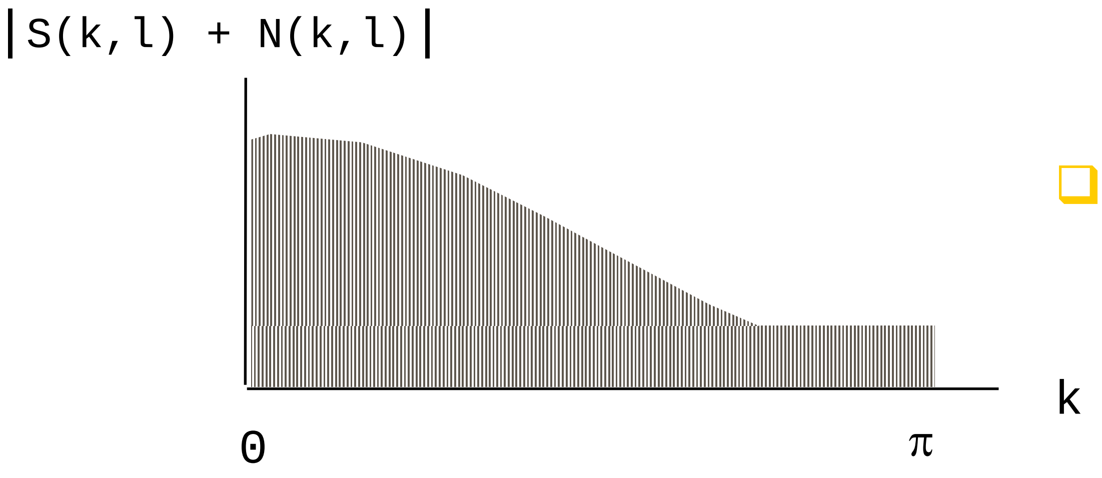
Image and Noise Spectral Properties

- Linearity of spectral representation

  If F(k, l) is the spectrum of image I(i, j)

  N(k, l) is the spectrum of noise n(i, j)

  Then, the spectrum of I(i, j) + n(i, j) is equal to F(k, l) + N(k, l)



- Once the spectrums are added, their separation is not a trivial task

Wiener Filter

- Wiener filter suppresses noise to minimise the error e^2 between the original signal s and the filtered out signal s_f that was corrupted by noise

  $$s_f(i) = w(i) \otimes (s(i) + n(i))$$

  $$e^2 = \Sigma(s_f(i) - s(i))^2$$

- In general, Wiener filter frequency response depends on image spectrum and noise spectrum

$$W(k,l) = F^*(k,l)/N(k,l)$$

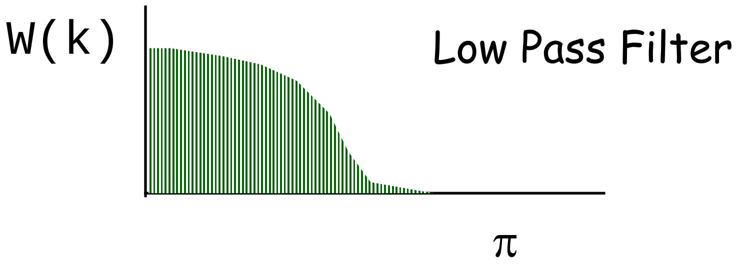
Thus, for white noise ($N(k,l)$ is const)

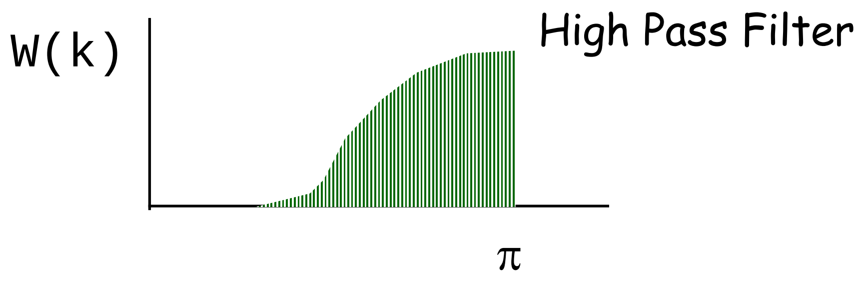
$W(k,l) = F^*(k,l)$ – The frequency response is complex conjugate of the image spectrum

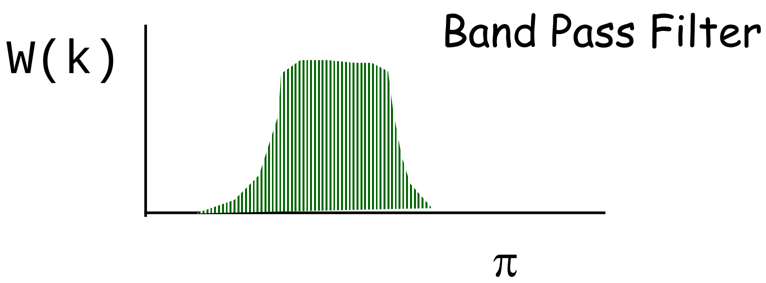
- Complex to calculate filter coefficients and implement in software
- To minimise the error, it must be adaptive because all image spectrums are different

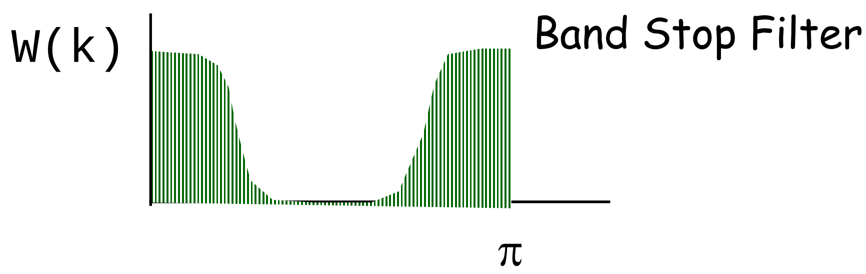
Filters

- Depending what part of the image spectrum is passed and what part of the spectrum is suppressed all filters can be divided into several groups
- 1D examples of possible frequency responses









Low Pass Filter (LPF)

- As a typical natural image spectrum is dominated by low frequency components, LPF can be a simple alternative to Wiener Filter
- There are several commonly used LPF kernels which combine reasonable noise suppression properties with low implementation complexity

0.11	0.11	0.11
0.11	0.11	0.11
0.11	0.11	0.11

0.07	0.12	0.07
0.12	0.25	0.12
0.07	0.12	0.07

- As the sum of all filter weights is equal to 1, the filters do not affect the average luminance
- Other odd size filters (5x5, 7x7) can also be used

Low Pass Filter (LPF)

Image corrupted by noise

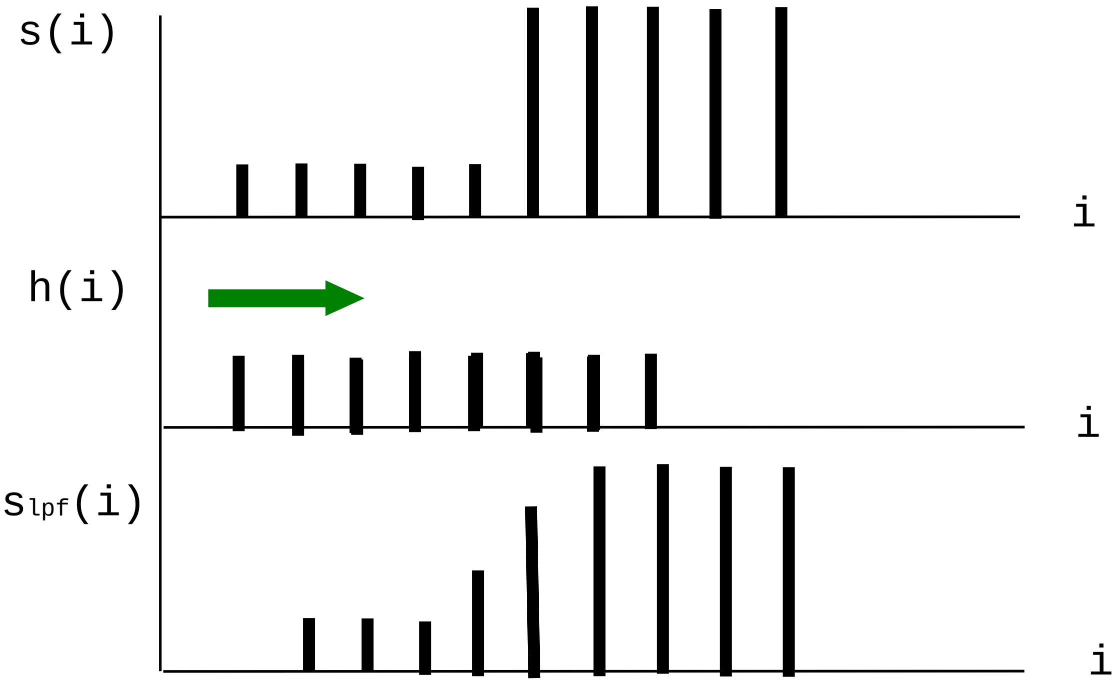
SNR = 20db

LP filtered image

SNR=26db

Low Pass Filter (LPF)

- Suppressing noise, LPF also affects the image
- If an image contains sharp edges of objects, they are blurred



Anisotropic Difusion

- An ideal noise suppression filter must
  1. Efficiently reduce noise level especially in uniform areas
  2. Do not blur object edges

- Anisotropic Diffusion is an adaptive filter that avoids LP filtering across object boundaries

	h_u	
h_l	1.0	h_r
	h_u	

where weights h are calculated based upon the difference between the adjacent image pixels in corresponding directions

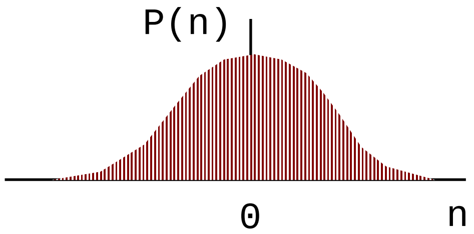
For example: the greater

$|\, s(i,j) - s(i-1,\ j) \,|$ the smaller h_l

- There are several Anisotropic Defusion filters that employ different equations to calculate h

Image Accumulation

- Statistical properties of white Gaussian noise are used as a basis for another noise suppression algorithm



$$\overline{n} = \sum p(n) * n = 0$$

- If several independent noise sequences are averaged, the result is a sequence of zero values (or nearly 0)

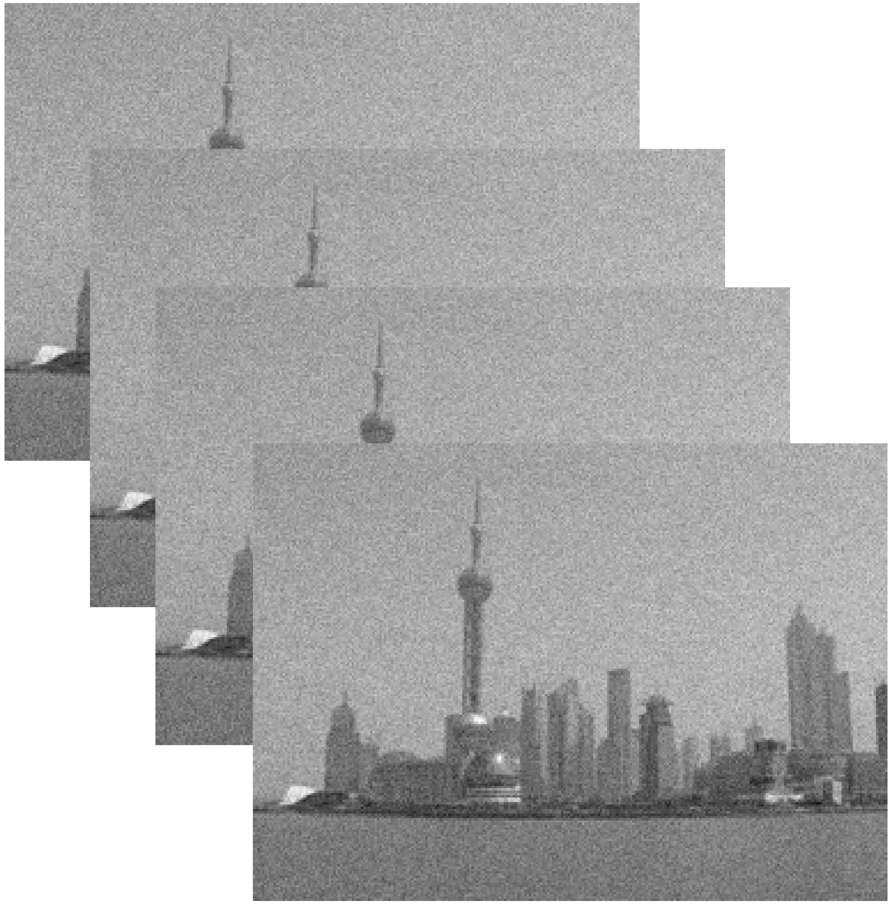
Example: Four images are taken sequentially. The camera and all objects are still within capturing interval

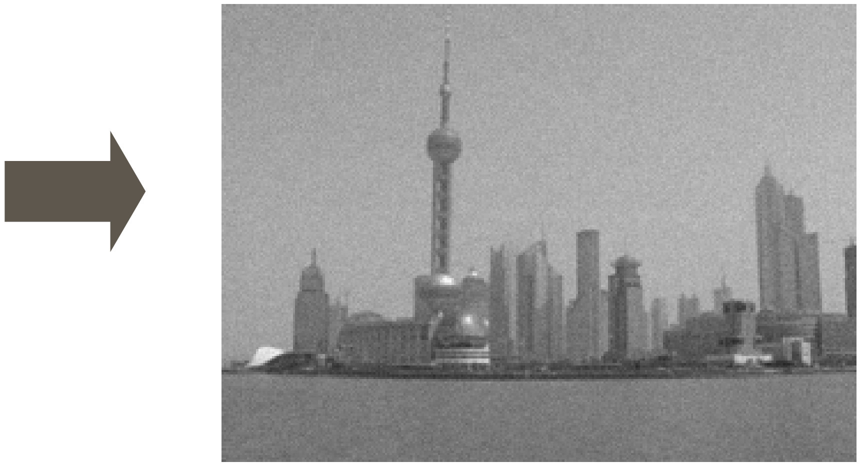
$$\sigma a = \sqrt{(0.25*\sigma)^2+(0.25*\sigma)^2+(0.25*\sigma)^2+(0.25*\sigma)^2} = \sqrt{4*0.0625*\sigma^2} = 0.5*\sigma$$

$$SNR = 20*log(Y/\sigma)$$

thus, leads to 3db SNR improvement

Image Accumulation





The averaged image has a better SNR without any blur introduced

(provided all objects are still)

Suggested Reading

- D Forsyth, Computer Vision. A Modern Approach
  - Chapter 7: Linear Filters

    7.1 Linear filters and convolution

    7.3 Spatial Frequency and Fourier Transforms

    7.4 Sampling and Aliasing

- G. Bradski, A. Kaehler, *Learning OpenCV*

  Chapter 5: Image processing