Image Analysis Tools
Biophysical Techniques Lecture Series 2020

Jérôme Boulanger
Light Microscopy

MRC-LMB
January 23, 2020

Outline

Outline

Resolution criterion

- The image of a point through a circular aperture is an Airy function

$$I(\theta) = \left(2 \frac{J_1(x)}{x} \right)^2$$

with $x = ka \sin\theta = k\mathsf{NA}r$, $k = 2\pi/\lambda$, a the aperture radius.

- Rayleigh criterion: Two points are separables if the maximum corresponds to the first minima of the other spot ($x \approx 3.83$):

$$\Delta_{xy} = \frac{0.61\lambda}{\mathsf{NA}}$$

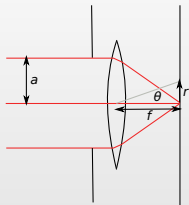Ex: $\mathsf{NA} = 1.42$, $\lambda = 520nm$, $\Delta = 208.68nm$
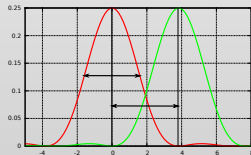

Fig. 1: Diffration by a circular aperture

Fig. 2: FWHM and Rayleigh

Resolution criterion

- The image of a point through a circular aperture is an Airy function

$$I(\theta) = \left(2\frac{J_1(x)}{x}\right)^2$$

with $x = ka\sin\theta = k\mathsf{NA}r$, $k = 2\pi/\lambda$, a the aperture radius.

- Rayleigh criterion: Two points are separables if the maximum corresponds to the first minima of the other spot ($x \approx 3.83$):

$$\Delta_{xy} = \frac{0.61\lambda}{\mathsf{NA}}$$

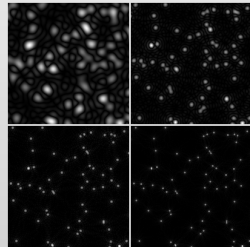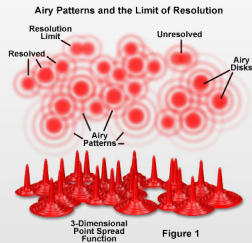Ex: $\mathsf{NA} = 1.42$, $\lambda = 520nm$, $\Delta = 208.68$nm

Fig. 1: Simulation of a field of point source.

Optical sectioning

- Slice in 3D by defocusing the sample

- Depth of field of the microscope:

$$\Delta_z \approx \frac{\lambda n}{\mathsf{NA}^2}$$

  with n the index of the medium between the coverslip and the objective

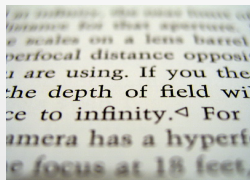- Many techniques exists to achieve optical sectioning (Confocal, TIRF, Structured Illumination)
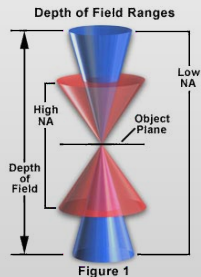

Fig. 2: Depth of field in photography

Fig. 3: Depth of field vs numerical aperture

Point Spread Function

Definition

- Image of a point source
- Impulse response of the optical system

Properties

- Characterize the aberation of the microscope
- The image of an object is the convolution of this object by the point spread funtion of the microscope

Gibson and Lanni theoretical model

- By computing the difference of optical path:

$$h(r, z) = \left| \frac{C}{d} \int_0^1 J_0 \left(\frac{ka\rho r}{z} \right) e^{\imath k \delta(\rho)} \rho \, d\rho \right|^2$$

with k wave vector $(2\pi/\lambda)$,$\delta(\rho)$ the optical path difference, $a = d\mathsf{NA}/\sqrt{\mathsf{M}^2 - \mathsf{NA}^2}$, NA the numerical aperture et M the magnification.

- Need to know all the parameters of the system

- May be able to adapt the model within the sample (spherical aberrations)


156   J. Opt. Soc. Am. A/Vol. 9, No. 1/January 1992
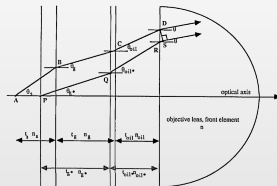
Fig. 1. Paths of rays from an on-axis point source to the front element of a high-magnification oil-immersion objective lens. $ABCD$ is a ray from a point source in a nondesign system that enters the front lens element at an angle θ when the object lies at a depth t_s in a medium of refractive index n_s, the coverslip has a thickness t_g and refractive index n_g, and the immersion oil has a thickness t_{oil} and refractive index n_{oil}. $PQRS$ is the corresponding ray in the design system and enters the front lens element at an angle θ. In the design system the point-source object is located immediately below the coverslip, the coverslip has a thickness t_{g*} and refractive index n_{g*}, and the oil-immersion layer has a thickness t_{oil*} and refractive index n_{oil*}.
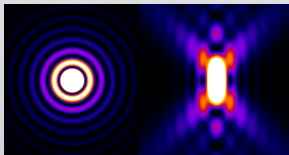
Experimental measure

- A measure of the impulse response can be obtained by acquiring the image of an object smaller than the resolution
- We can use fluorescent beads or gold particle mounted in a medium similar to the one used to image the sample.
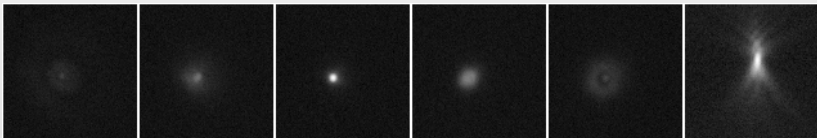

Fig. 4: Axial and lateral view of a fluorescent bead (100nm) using a widefield microscope.

- Drawbacks
  - Noisy measures
  - Need to have exactly the same condition than the sample (pixel size, binning, wavelength, mounting medium,…)
- Advantage:
  - Can capture complex aberrations due to the imperfection of the objective (but better hope the objective is in good state.)

Linear shift invariant system

- The output of a **linear shift invariant** system is the convolution of the input by the impulse response of the system

Input $\longrightarrow$ System $\longrightarrow$ Output

Fig. 5: Linear shift invariant system
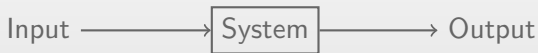
- If we approximate the microscope as a LSI, then the acquired image is the **convolution** of the PSF and the sample.

Sample $\longrightarrow$ Microscope $\longrightarrow$ Image

Fig. 6: Linear shift invariance approximation

- Counter example: spherical aberrations are function of depth

Linear shift invariant system

- The output of a **linear shift invariant** system is the convolution of the input by the impulse response of the system

Input ⟶ | System | ⟶ Output

Fig. 5: Linear shift invariant system

- If we approximate the microscope as a LSI, then the acquired image is the **convolution** of the PSF and the sample.

Sample ⟶ (∗) ⟶ Image

PSF
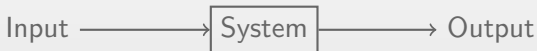
Fig. 6: Linear shift invariance approximation

- Counter example: spherical aberrations are function of depth

Convolution

- **Linear combination** of intensity values for neighbours

$$I[n] = a \cdot I[n-1] + b \cdot I[n] + c \cdot I[n+1]$$

- Coefficients $[a, b, c]$ define an array h called **filter**:

$$I[n] = h[0] \cdot I[n-1] + h[1] \cdot I[n] + h[2] \cdot I[n+1]$$

- We often denote $h * I$ the convolution of I by h.
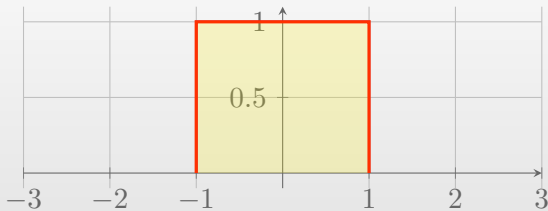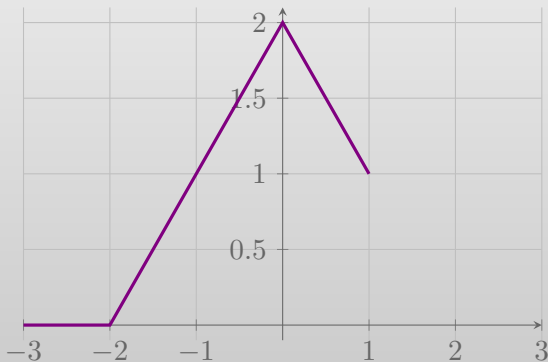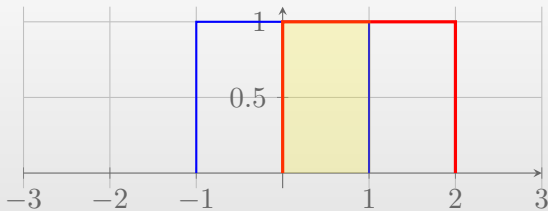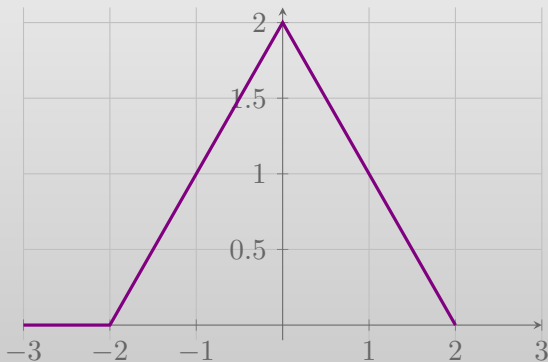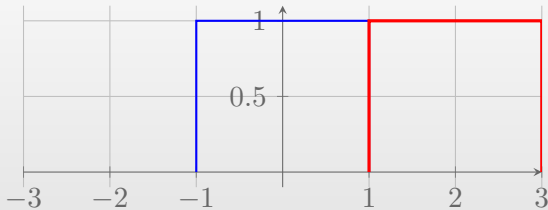

Fig. 7: Convolution by a 3x3 filter

1D Example

Convolutions of two rectangular functions
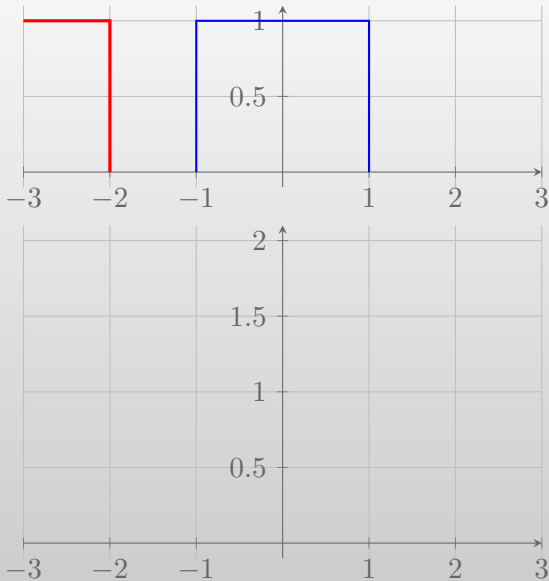
1D Example

Convolutions of two rectangular functions
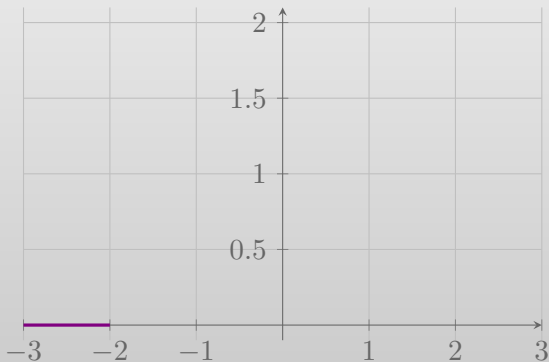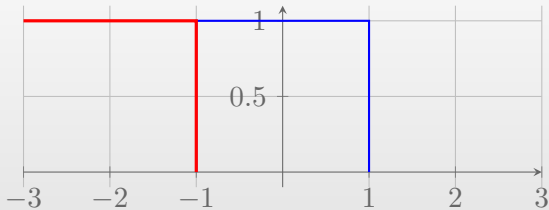
1D Example

Convolutions of two rectangular functions
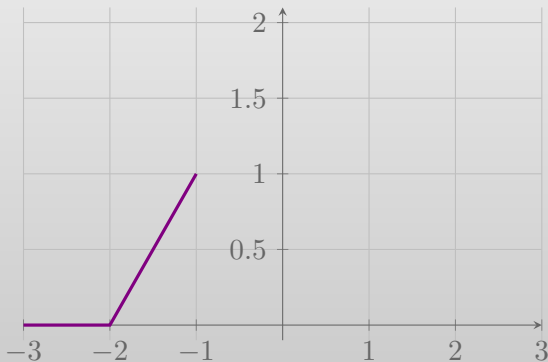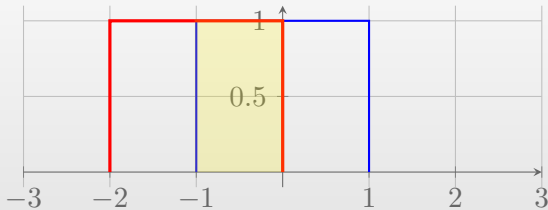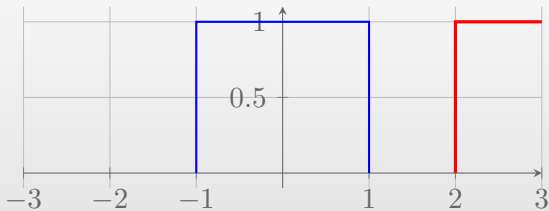
1D Example

Convolutions of two rectangular functions

1D Example

Convolutions of two rectangular functions

1D Example

Convolutions of two rectangular functions

1D Example

Convolutions of two rectangular functions
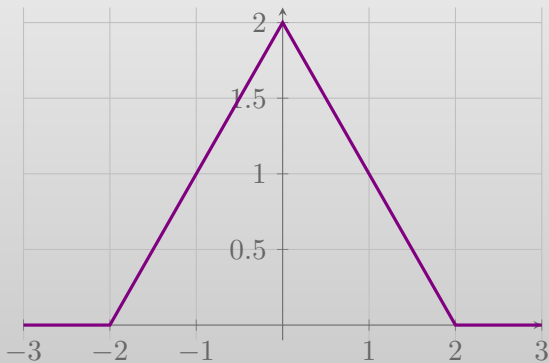
Thick brush

- The convolution can be seen a brush in used for painting
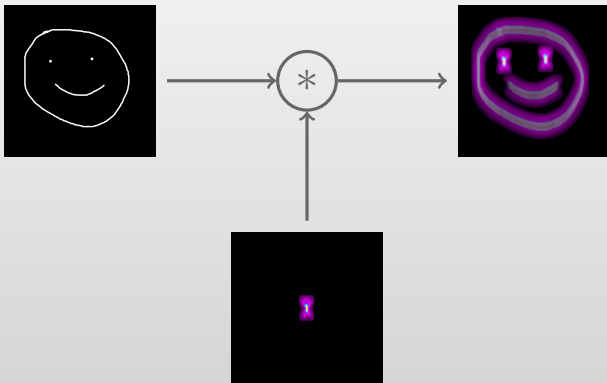
Decomposition in sine waves

- Square wave as sum of sine function:

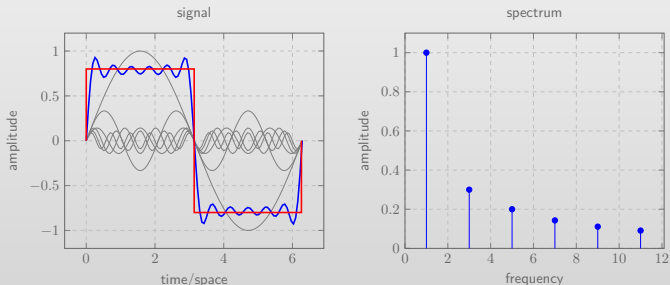$$f(x) = \sum_{n=1}^{\infty} \frac{1}{n} \sin nx = 1 + \sin(x) + \frac{1}{3}\sin(3x) + \frac{1}{5}\sin(5x) + \cdots$$

Fig. 8: Rectangle function decomposed into a serie of sine function.

Frequency domain

- Discret Fourier Transform

$$\tilde{I}_k = \sum_{n=0}^{N-1} I_n \cdot (\cos(-2\pi kn/N) + i\sin(-2\pi kn/N))$$

- The **Fast Fourier Transform** allows to speed-up the computation

- Spatial information "lost"

- Convolution $\Leftrightarrow$ Multiplication
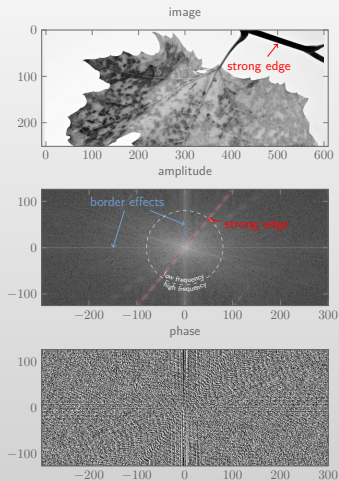
Fig. 9: Amplitude and phase of the Fourier transform of the top images.

Optical transfer function

Definition
The **optical transfer function** is the Fourier transform of the point spread function.

Properties

- Complexe values
- Contains the same information that the point spread function
- The modulus is called the **modulation transfer function**
- Its value vanishes beyond the cut-off frequency (resolution limit)
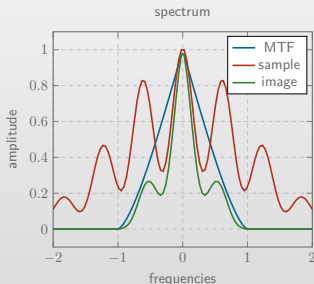
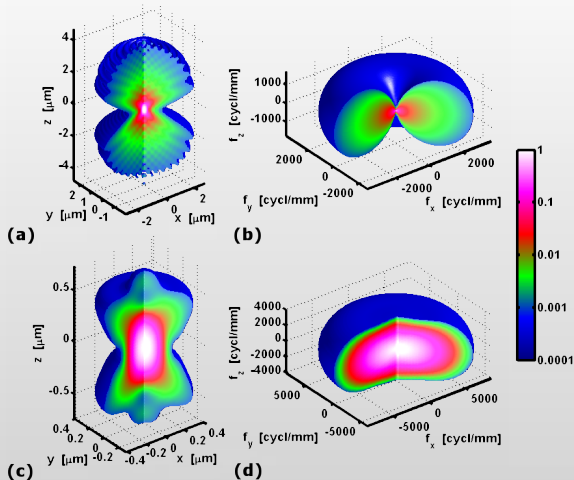Fig. 10: MTF in 2D computed as the autocorrelation of a disk.

Widefield & Confocal PSF

Fig. 11: The three-dimensional point spread functions (a,c) and corresponding modulation transfer functions (b,d) of a wide-field microscope (a,b) and confocal microscope (c,d). In both cases the numerical aperture of the objective is 1.49 and the refractive index of the medium 1.52. The wavelength of the emitted light is assumed to be 600 nm and, in case of the confocal microscope, that of the excitation light 500 nm with circular polarization. The colors as shown on the logarithmic color bar indicate the irradiance (a,c) and spectral density (b,d) normalized to the maximum value. (cc) Tom.vettenburg at English Wikipedia

Spherical aberrations

- The rays on the edge of the lens do not intersect at the same point than the ones coming from the center.
- Microscope objectives are corrected for spherical aberrations
- In practice spherical aberration comes from
    - index mismatch (use the right lens: oil/water/air)
    - coverslip thickness (objectives are optimized for 0.17mm coverslip)
    - depth (across the z-stack, the PSF is varying due to the intermediate layers of different refractive index)
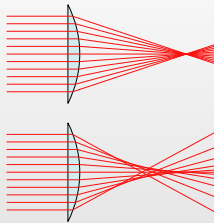
Fig. 12: Origin of spherical aberration.
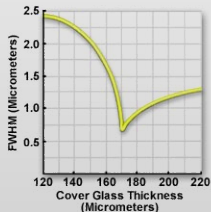
Fig. 13: Cover glass thickness vs half-width intensity distribution. © http://www.olympusmicro.com

Spherical aberrations

- Characterized by an asymmetry in axial (Z) direction
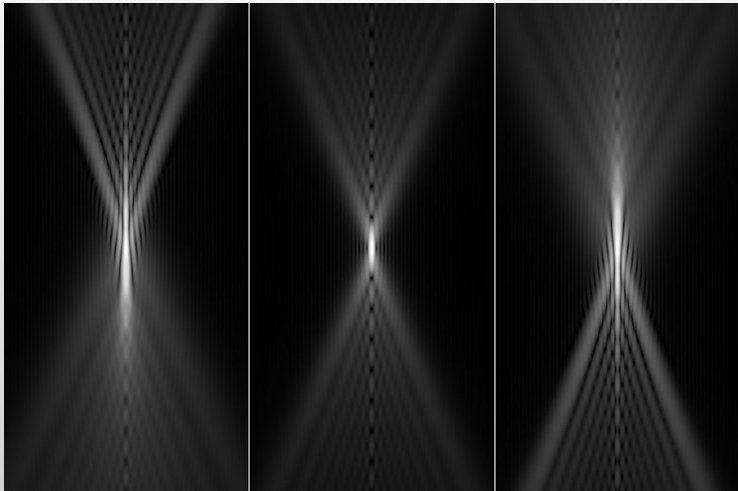
Fig. 14: Longitudinal sections through a focused beam with negative (top row), zero (middle row), and positive spherical aberration (bottom row). The lens is to the bottom.

Chromatic aberrations

- The refractive index of materials depends on the wavelength λ
- The focus point of the lens depends on λ
- High quality objective are corrected for achromatism by combining doublet of lens (flint/crown)
- A change of dichroic filter might affect the lateral position of the focal point
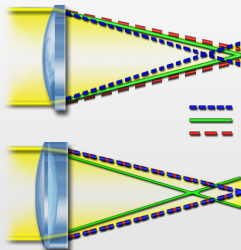
Fig. 15: Axial chromatic aberration © www.microscopyu.com
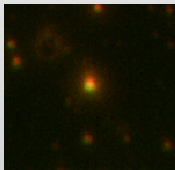
Fig. 16: Image of a Tetraspeck beads preparation green and far red channels © Nick Barry.

Noise sources

Definition [signal processing]

In signal processing, noise is defined as un-wanted signal…

- Out of focus light, autofluorescence, dark current, shot noise, hot pixels?

Definition [statistic]

Noise is the variation of signal obtained by repeating the measurement.

- **shot noise**: the counting process lead to a Poisson distribution for the number of generated photo-electrons.
- **dark current**: even in the total obscurity, photo-electron are created and generate a tiny current
- **read-out**: errors made when measuring the voltage at each pixel

Random measurements
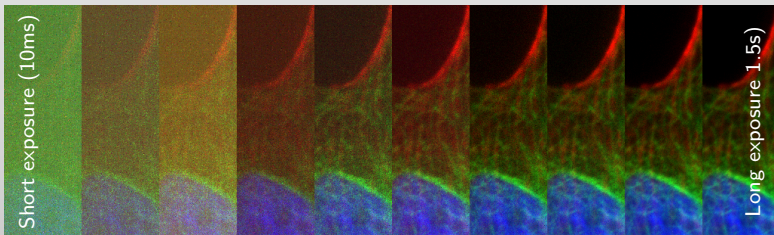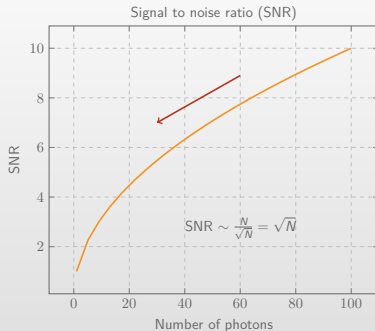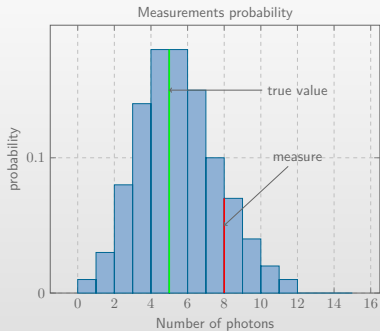
Noise model & characterization

Assuming for each pixel i of the image:

$$Y_i = g_0 N_i + \varepsilon_i$$

where

- Y_i intensity
- $N_i \sim \mathcal{P}(\mu_i)$ # photo-electron
- $\varepsilon_i \sim \mathcal{N}(m, \sigma_\varepsilon^2)$ thermal fluctuations

this leads to

$$\text{Var}[Y_i] = g_0 \, \mathbb{E}[Y_i] + \underbrace{\sigma_\varepsilon^2 - g_0 m}_{e_{DC}}$$

Variance stabilization transform

$$\mathcal{T}(Y_i) = \tfrac{2}{g_0} \sqrt{g_0 Y_i + \tfrac{3}{8} g_0^2 + e_{DC}} \quad \sim \quad \mathcal{N}(0,1)$$
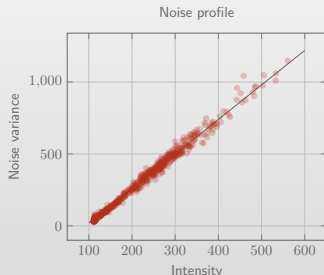
Noise profile

Fig. 17: Noise variance vs intensity empirically measured on a sCMOS camera.

Background and uneven illumination

- Intensities are corrupted by a background and an non-uniform illumination profile.
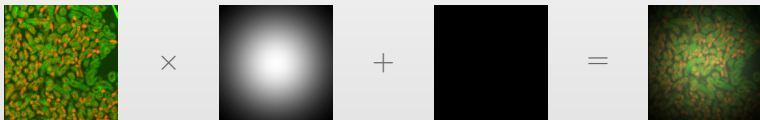
- Non uniformity introduces
  - **bias** in intensity quantification
  - problem when tiling images.
- Background subtraction is not valid and make things worse in some case.

Summary

The microscope produces blurred and noisy images...

Outline

Non-local image denoising

Non–Local Means principle

- Compare **patches** instead of pixels
- Average repeats in a large neighborhood
- Minimize the sum of the difference between patches

Iterative refinement

- Growing **4D** neighborhood
- Statistical patch distance
- Bias-variance trade-off
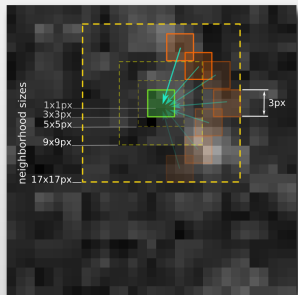
Fig. 18: Patch exploration

Denoising benchmark

Using acquired images

3.5s exposure time
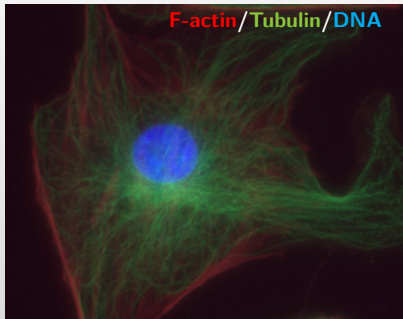
50ms exposure time
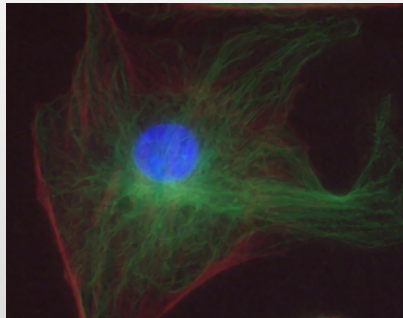
3.5s exposure time   50ms exposure time denoising

Signal-to-noise improvement
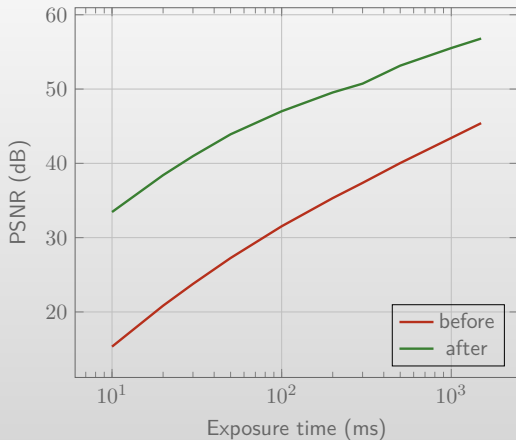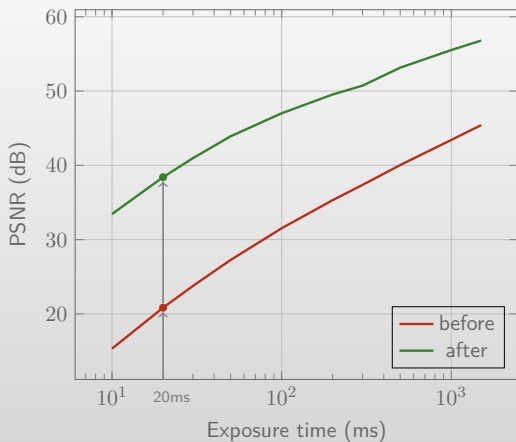
Signal-to-noise improvement
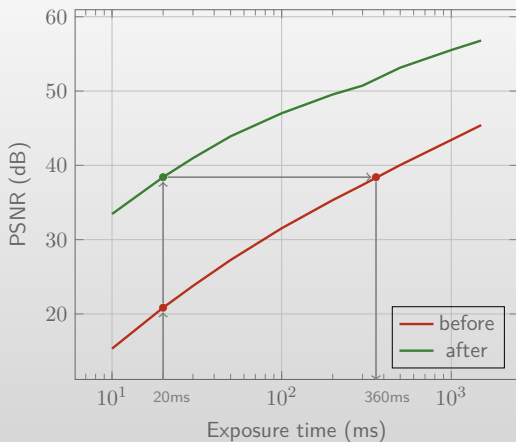
Signal-to-noise improvement

Signal-to-noise improvement
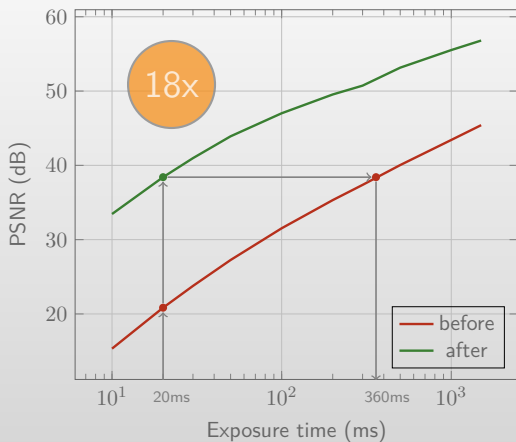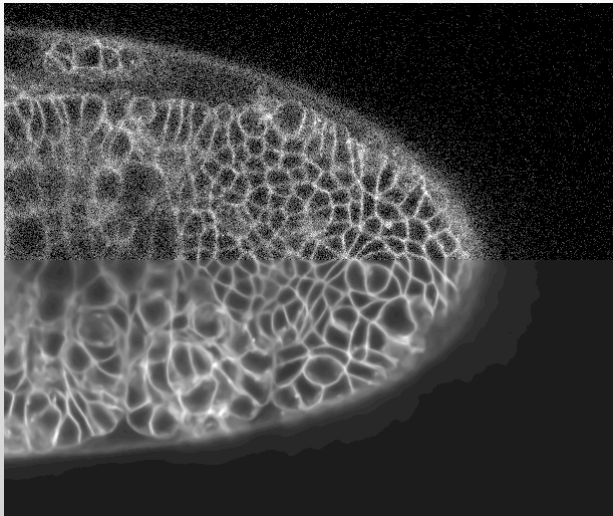
Fig. 19: Confocal image of developing Drosophila – Yara Sanchez-Corrales

Denoising from ImageJ/Fiji

- Integration as a macro
- Calling the native code
- Runing locally
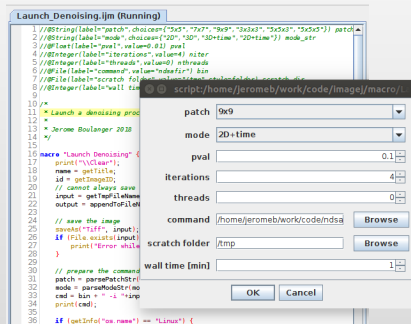
Fig. 20: Denoising interface and macro from Fiji

Batch processing on the cluster

1) copy the software on istore
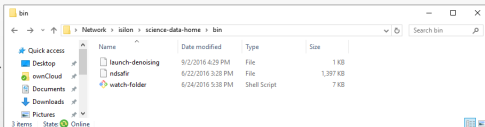
2) copy the images on istore

3) launch the command

Istore

node #1

PC

hex

...

node #3000
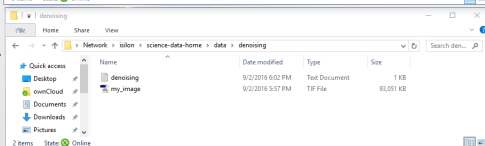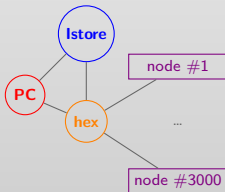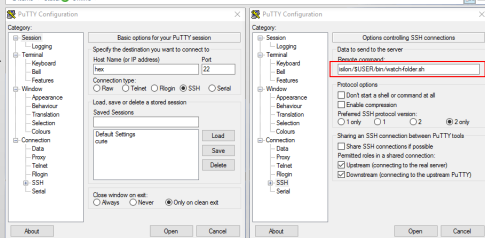
nd-safir software

n-dimensional spatially-adaptive filtering

- Process multi-dimensional data (5D)
- Parallel software rewritten (c++) at MRC-LMB
- Running on the cluster (single node) with helper scripts
- Bridge with ImageJ/Fiji

Integration in commercial solutions:

- OMERO image management tool
- OMX
- Metamorph plugin (Roper Scientific SAS)
- Photometrics Prime Enhance sCMOS camera (FPGA)

Outline

Deconvolution with Huygens
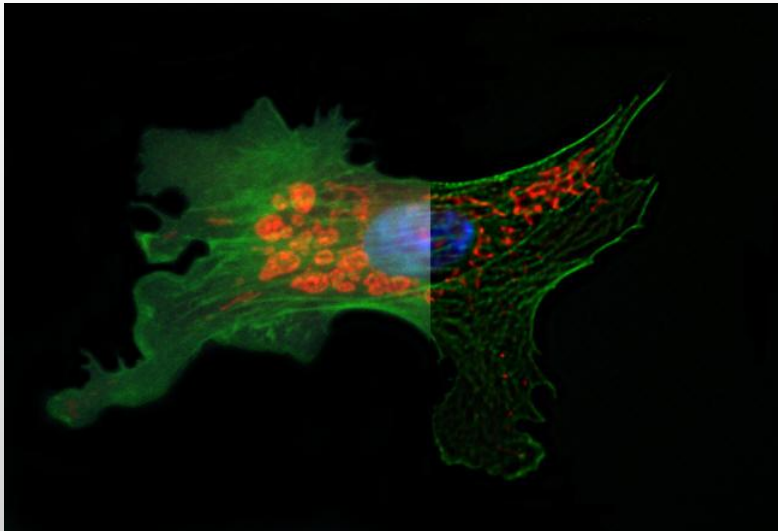
Fig. 21: Before (left) and after (right) deconvolution images. Experimental point spread functions were generated for the red, green, and blue channels on an epifluorescence microscope and then used to deconvolve a standard Invitrogen Fluocells #1 prepared slide, containing bovine pulmonary artery endothelial cells stained for mitochondria (red), F-actin (green), and nuclei (blue).

Why is it difficult?

- Convolution is equivalent to a multiplication by the OTF in Fourier space:

$$F = H \times U$$

- Can we deconvolve an image by dividing the image by the OTF?

$$U = \frac{F}{H}$$

- We saw that
  - The OTF vanishes beyond the resolution limit.
  - The noise kicks in even before this limit and would be amplified.

- Deconvolution is an "ill-posed" problem, we need to add constraints:
  - Positivity,
  - Smoothness (limit the number of iterations/add constraints).

Deconvolution algorithm
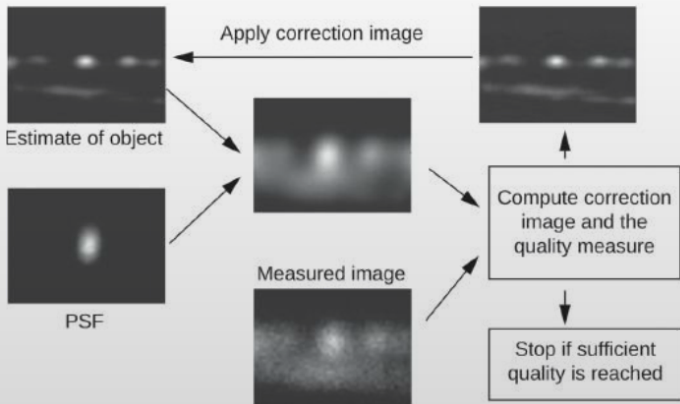
Huygens: step by step

1. Load the data (keep original format & metadata)
2. Edit the parameters
3. Inspect the data (hot pixels, saturation)
4. Define a PSF (theoretical vs measured)
5. Launch a deconvolution (several algorithm available)
6. Inspect the result (3D rendering, twin slicer)
7. Perform a chromatic correction

Main interface

Microscopy parameters

- Display the required informations related to the acquisition
- Indicate if these parameters are consistent
- Can be read in from metadata which accompany the RAW images.
- Keep the data in the original format
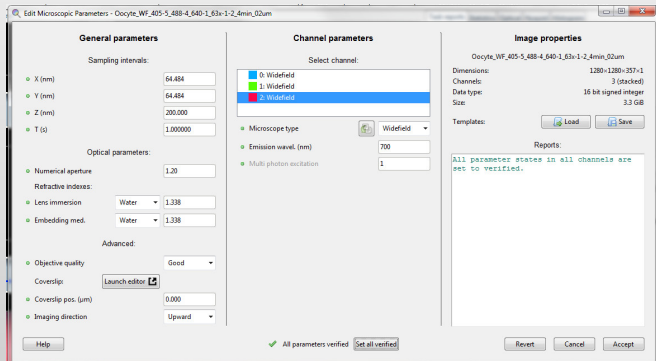
Algorithm selection and tuning

Twin slicer

- Synchronize views of 2 images
- Allows to inspect the image after deconvolution
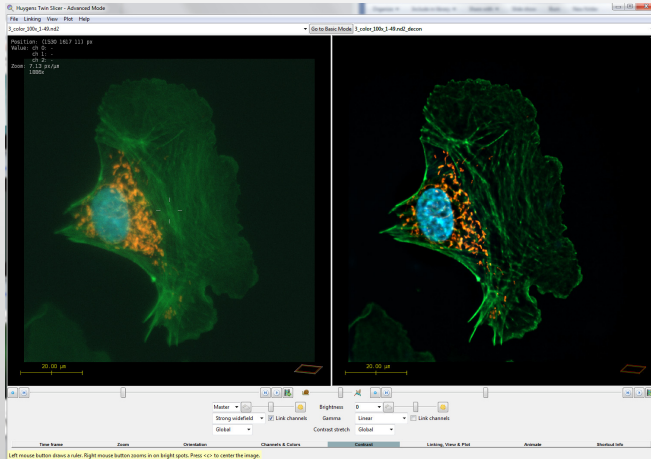
Simulated Fluorescence Process renderer

- Simulates how the object's excited matter emits light forming a scene
- Based on ray tracing
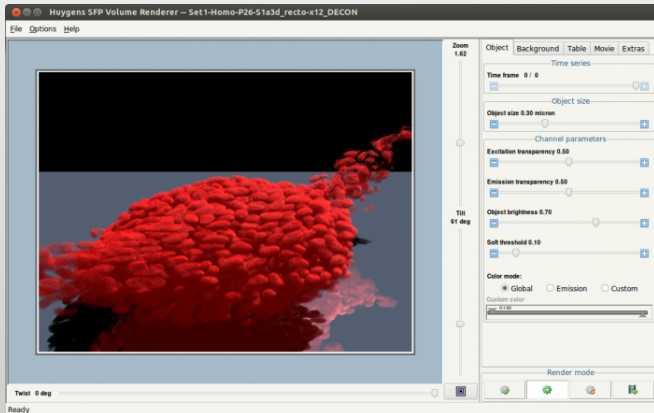
Chromatic Aberration Corrector

- Register channels using
  - Cross correlation
  - Center of mass
- When performed after deconvolution, the higer SNR improves the registration
- Improves colocalization analysis
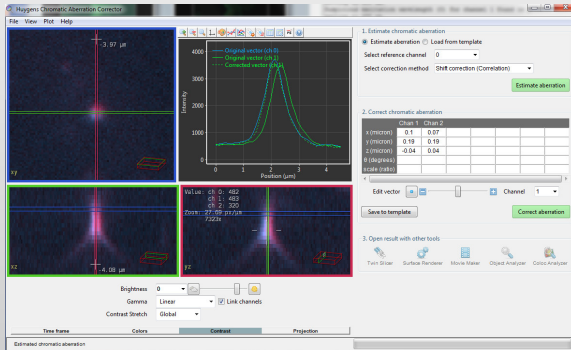
STED deconvolution

- Not only wide-field image can be deconvolved
- Huygens supports various imaging modality
  - Wide-field
  - Confocal
  - Light-sheet
  - STED
- Due to the non-linearity of the deconvolution process, extra resolution can be claimed.
- Here the lateral jitter correction, proved essential in improving the image quality.
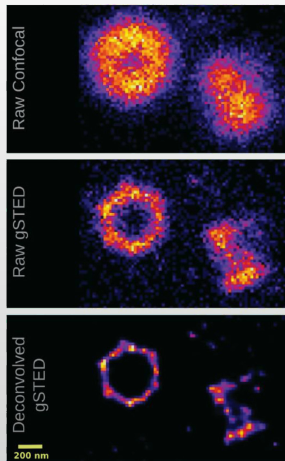
Fig. 22: FWHM improvement toward 22nm ©Microscopy Today Nov 2013

DeconvolutionLab2 & PSF Generator

- Combine DeconvolutionLab2 and the PSF Generator plugin to deconvolve images
- Need to manually check background level
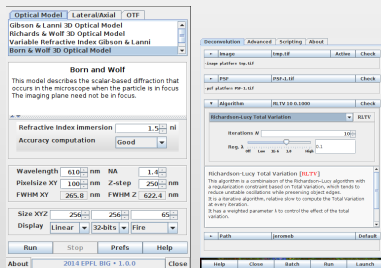
Fig. 23: PSF Generator from Fiji

Outline

Bitplane Imaris

- Organize (group/conditions)
- Visualize (Volume rendering, isosurfaces)
- Analyze (spot detection, tracking, segmentation)
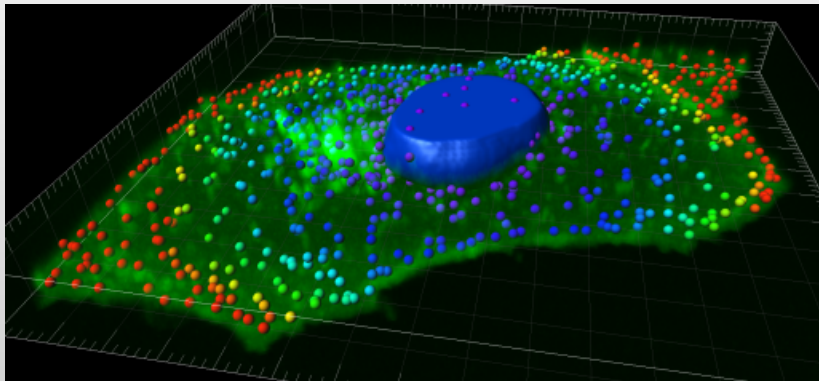
Organize

- All data are stored in an **Arena**
- Files can be grouped in an **assay** which can contain several **groups**.
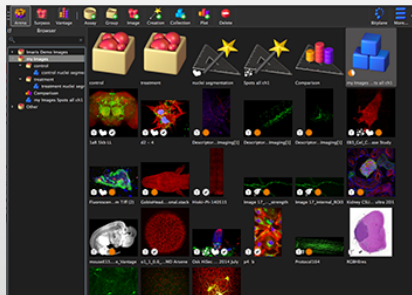
Visualization

- A scene can be composed of several objects
  - Digital rendering
  - Surfaces
  - Spots (3D balls)
  - Tracks (3D filaments)
- A movie editors allows to create 3D animations easily
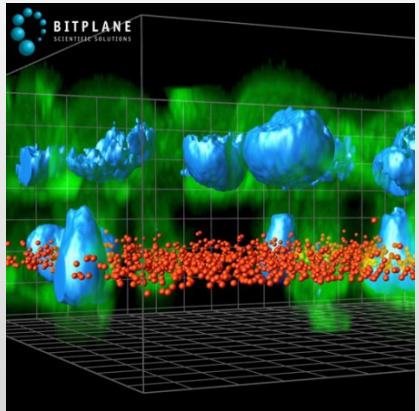
Image analysis

- Several analysis methods are available:
    - Spot detection and tracking
    - Segmentation
    - Neuron tracing
- You can then export extracted measurements
    - to Excel
    - via ImarisXT to make a bridge with Matlab
- Or use the statistical data plotting in Imaris.
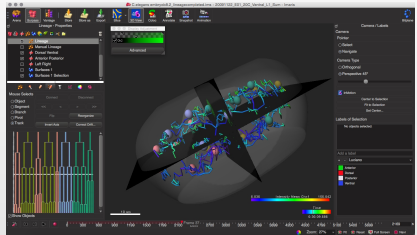
Fig. 24: Spot tracking and visualization in Imaris
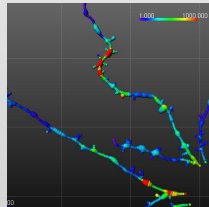
Fig. 25: Neuron tracing feature in Imaris

Outline

Image analysis softwares

- Analysis room located in room 1N120
- Softwares:
  - SVI Huygens (2)
  - Bitplane Imaris (3)
  - Nikon NIS Element General Analysis (1)
  - Offline version of
    - Leica LAS
    - Nilon NIS Element
    - Zeiss Zen
  - ImageJ/Fiji (6)
  - Mathworks Matlab (1)
  - R (1)
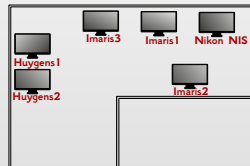
Fig. 26: Analysis room 1N120

Data management

- Acquisition stations
  - Temporary (regular clean up)
  - When disk are full the system slows down
- Temporary storage `micro-nas-1`
  - $\sim$ 14TB NAS
  - **Shared** with all users
  - Temporary (regular clean up)
  - No mirroring (less secure)
  - RAID (support disk failure)
  - Good for exchanging data with us
- Long term achiving with `istore`
  - 500GB max
  - **secure** (mirrored outside the building)
  - accessible only by you
  - Good for keeping published raw data

Getting Help & Training

- **Subscribe** to the confocal list by sending a email to listmanager@mrc-lmb.cam.ac.uk with the text "subscribe confocal-list" in the message body.
- Book a **training** on an advanced imaging software
  - Huygens (Jon, Jérôme, Nick)
  - Imaris (Jon, , Jérôme, Nick)
  - Nikon NIS Element (Nick)
- Attend a **course**
  - Introduction to ImageJ macro programming (Jérôme)
  - Mastering Nikon NIS Element general analysis (Nick)
  - Introduction to image processing (Jérôme)
- Come in and have a **chat** (room 2S459)
  - We can help with your ImageJ macro (debug/custom script)
  - Create specific analysis procedure (ImageJ/Matlab/R/C++)

Online learning ressources

- ImageJ
    - http://imagej.nih.gov
    - http://fiji.sc
    - http://cmci.embl.de/documents/ijcourses
    - https://github.com/jboulanger/
      introduction-to-imagej-macros/releases/tag/1.0.0
- SVI Huygens https://svi.nl
    - register to the wiki
    - get in touch directly with SVI team (TCL scripting)
- Bitplane Imaris http://www.bitplane.com/learning
    - Step-by-step tutorials
    - Webinars
    - Case studies

Acknowledgment

Light Microscopy Facility

- Nick Barry
- Jon Howe
- Ben Sutcliffe
- James Manton

At LMB

- Liam Cheeseman
- Yara Sánchez-Corrales
- Agata Zielinska
- Adam Tozer
- Jake Watson