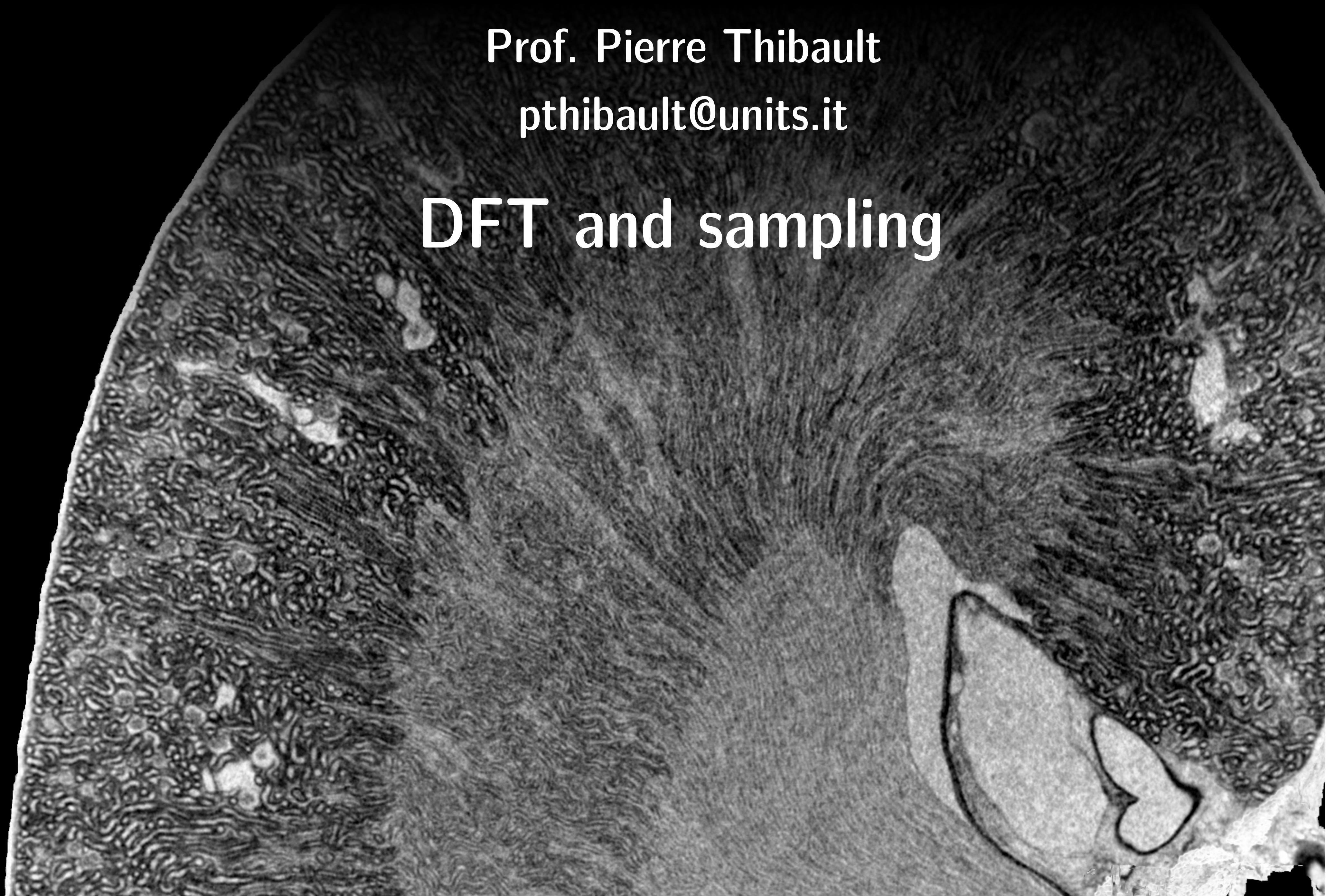
Image Processing for Physicists

Prof. Pierre Thibault

pthibault@units.it

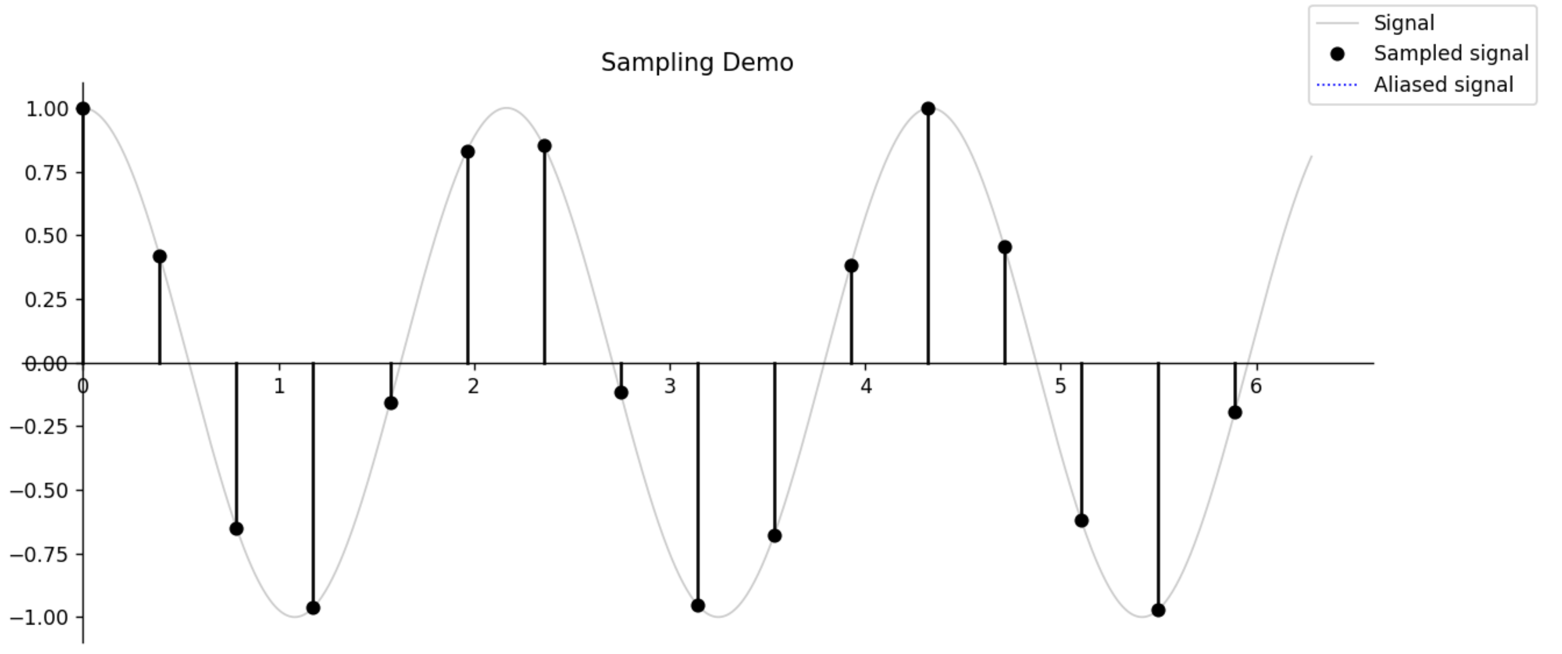
DFT and sampling

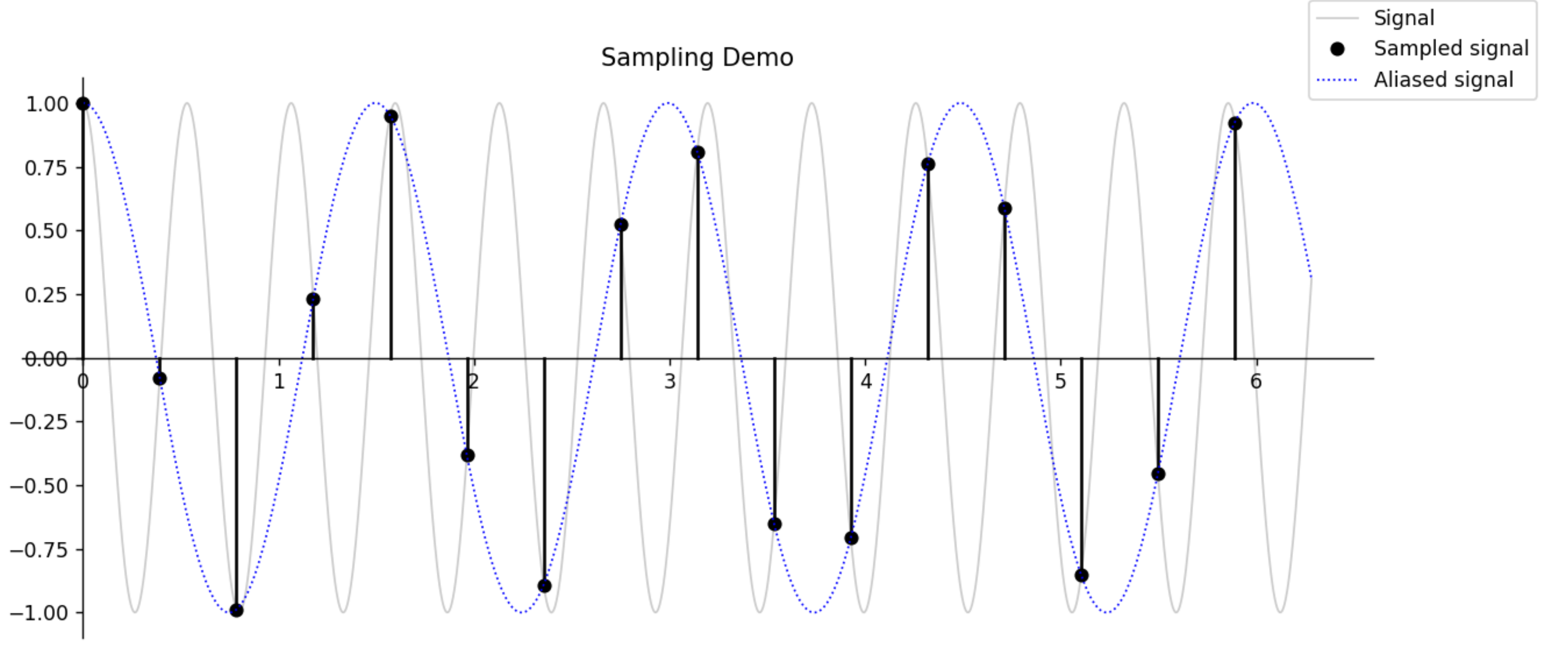


Overview

- Sampling
  - Nyquist theorem
- Discrete Fourier transform
  - Undersampling and Aliasing
- Interpolation (resampling)

Sampling


Sampling Demo
Signal
Sampled signal
Aliased signal
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
0
1
2
3
4
5
6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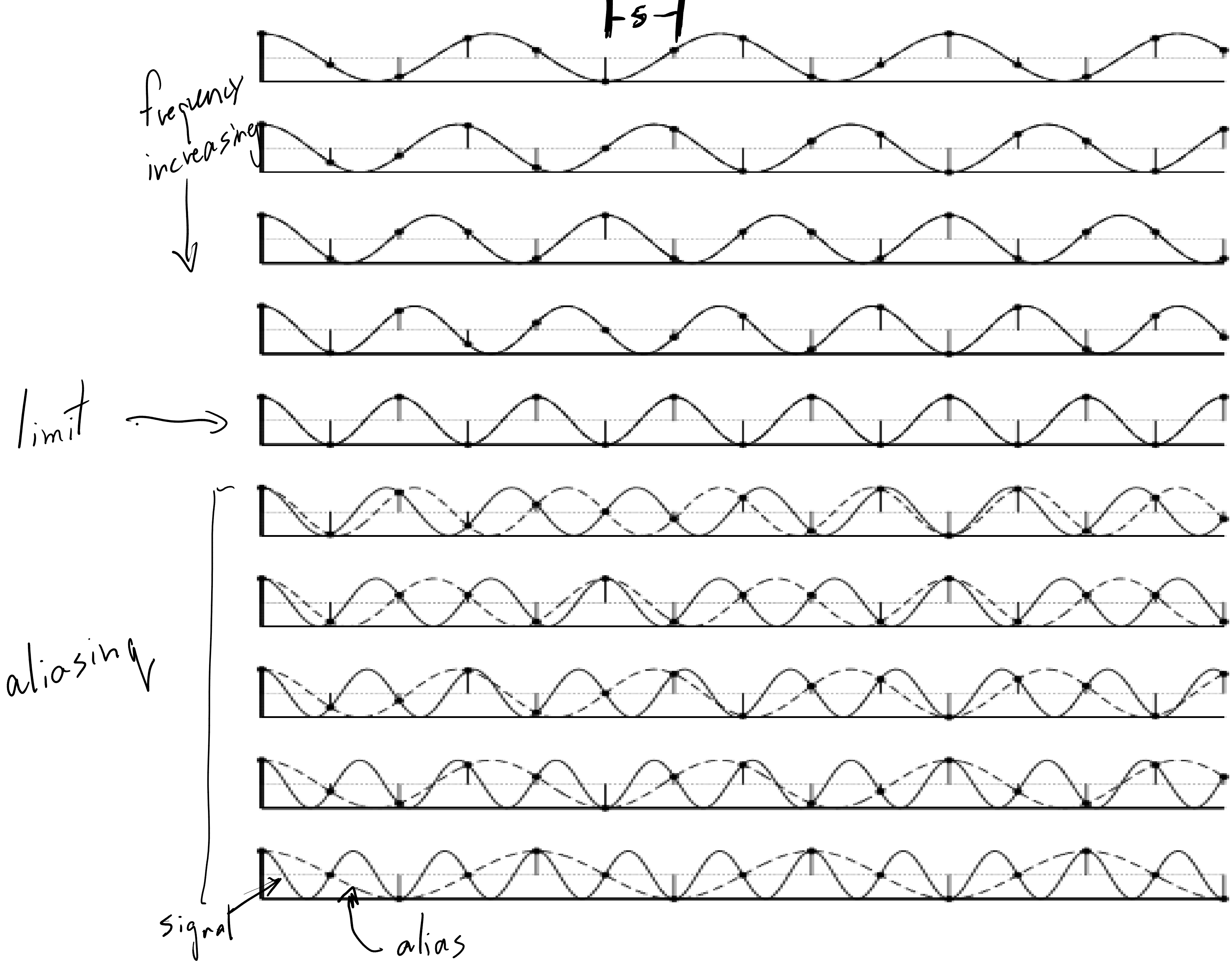
6

Undersampling and aliasing



The Nyquist-Shannon sampling theorem

"The largest frequency that can be represented in a signal sampled at intervals s is 1/2s"

sampling rate (sampling frequency) : $\frac{1}{s}$

Nyquist frequency = $\frac{f}{2}$

Periodic signals

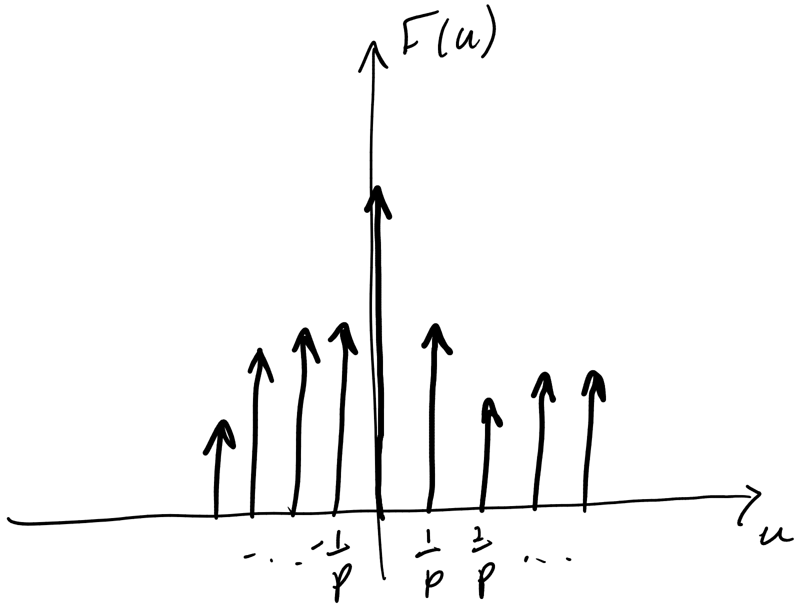
$f(x)$: periodic with period p

$$f(x) = \sum_{k=-\infty}^{\infty} c_k e^{2\pi i x k/p}$$ Fourier series

What is the continuous Fourier transform of $f(x)$?

$$F(u) \int_{-\infty}^{\infty} f(x) e^{-2\pi i u x} dx = \int_{-\infty}^{\infty} \sum_{k=-\infty}^{\infty} c_k e^{2\pi i x k/p} e^{-2\pi i u x} dx$$

$$= \sum_{k=-\infty}^{\infty} c_k \underbrace{\int_{-\infty}^{\infty} e^{2\pi i x \left(\frac{k}{p} - u\right)} dx}_{\delta\left(\frac{k}{p} - u\right)}$$

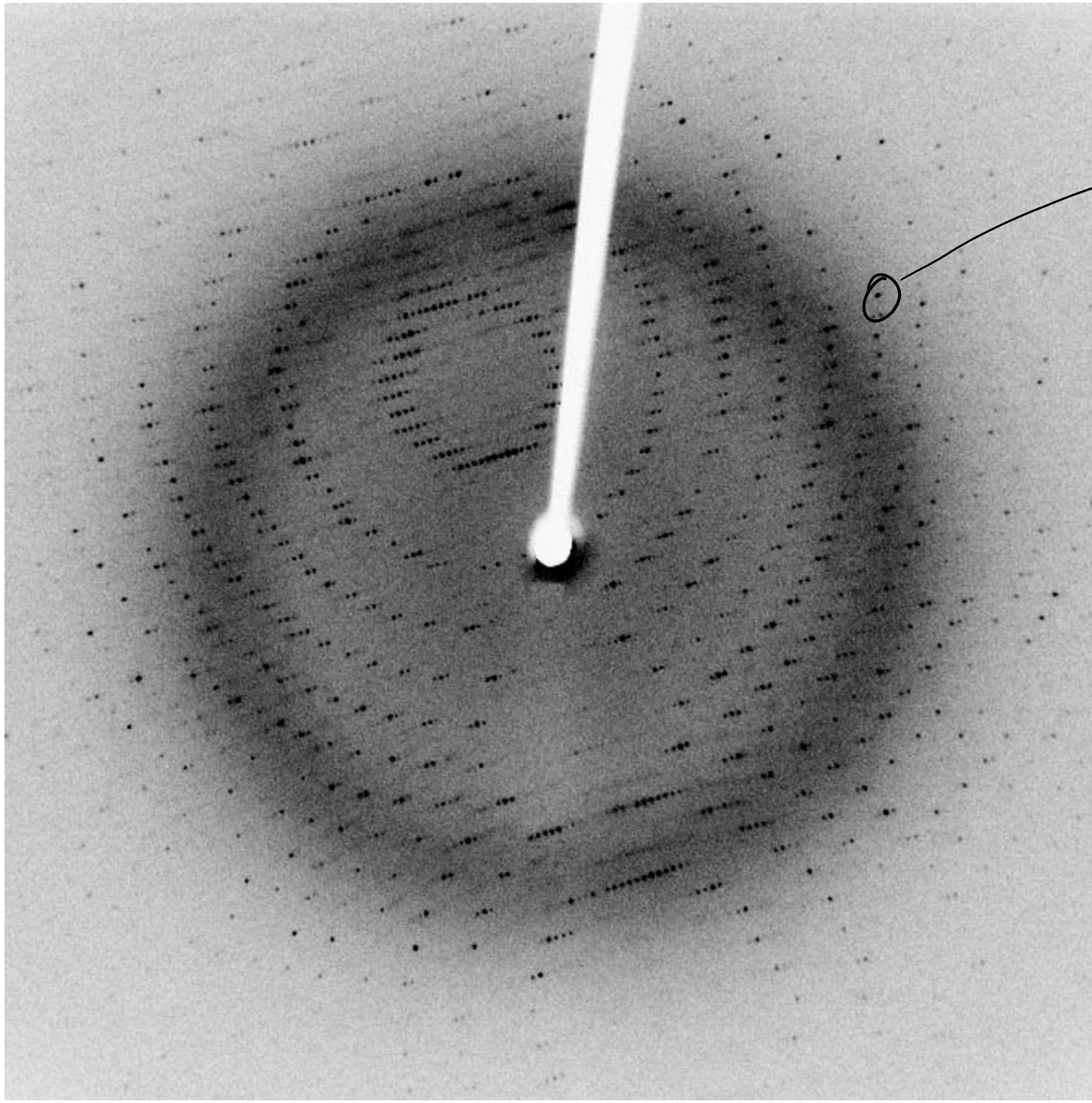


$$F(u) = \sum_{k=-\infty}^{\infty} c_k \, \delta\left(u - \frac{k}{p}\right)$$

$\Rightarrow$ F.T. of a periodic function has non-zero amplitude at u = multiples of $1/p$

Periodic signals

X-ray diffraction by a crystal

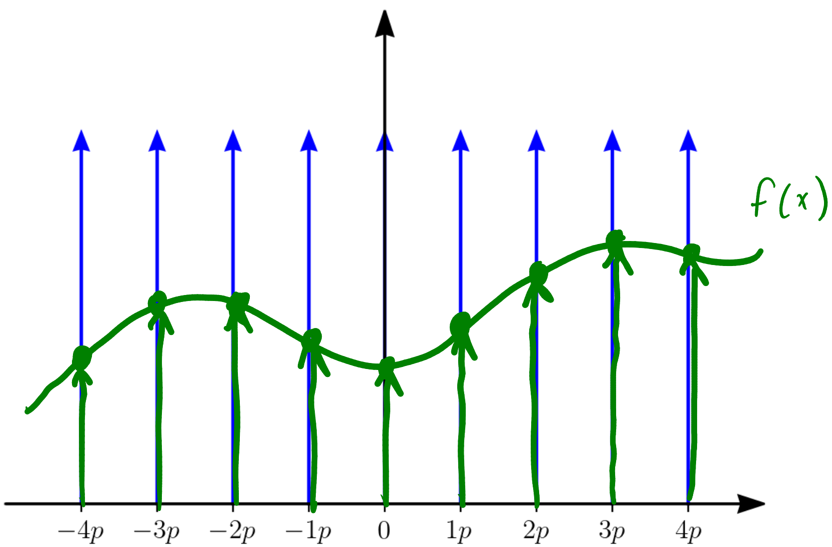


Bragg peaks

Sampling with the Dirac comb

A periodic function made of Dirac functions

$$\Delta_p(x) = \sum_{n=-\infty}^{\infty} \delta(x - np)$$



$\Delta_p(x)$ can be used to represent the sampling process:

$$f(x)\,\Delta_p(x) = \sum_{n=-\infty}^{\infty} f(x)\,\delta(x-np) = \sum_{n=-\infty}^{\infty} \underbrace{f(np)}_{f_n}\,\delta(x-np)$$

Fourier transform of a Dirac comb

Fourier series of $\Delta_p(x)$:

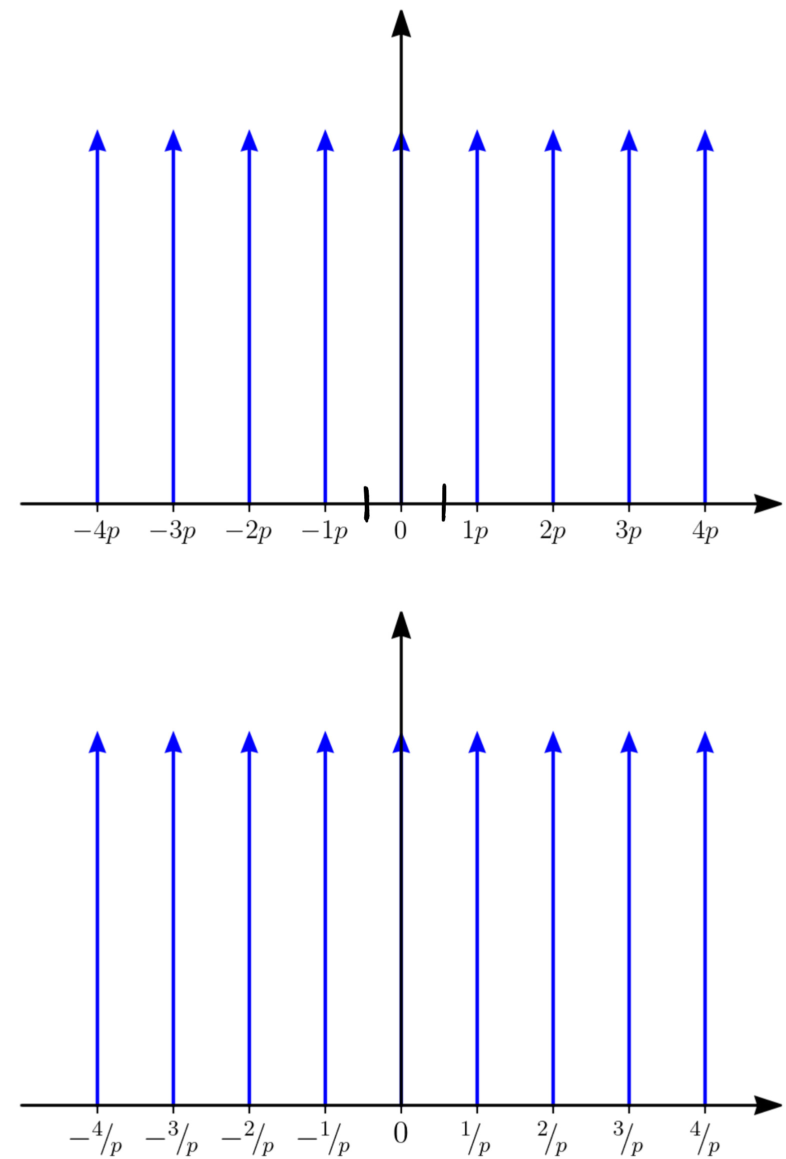
$$C_k = \int_{-\frac{p}{2}}^{\frac{p}{2}} \Delta_p(x)\, e^{-2\pi i k x / p}\, dx$$

$$= 1$$

$$\mathcal{F}\{\Delta_p(x)\} = \sum_{k=-\infty}^{\infty} \overset{1}{C_k}\, \delta\left(u - \frac{k}{p}\right)$$

$$= \Delta_{\frac{1}{p}}(u)$$

Fourier transform of a Dirac comb is a Dirac comb

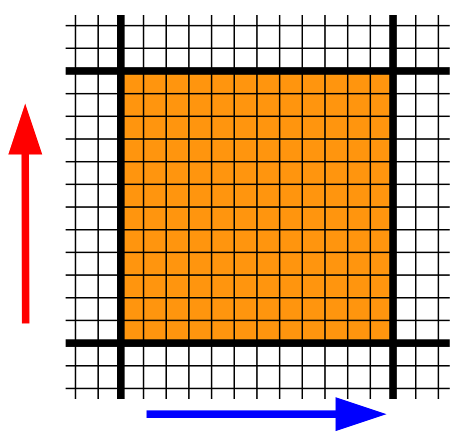


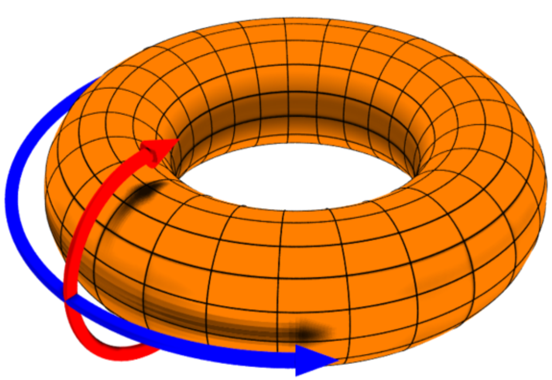
Discrete Fourier Transform

- A **periodic** function has a **discrete** spectrum in the Fourier domain;

- A function with **discrete** values in the spatial domain is **periodic** in the Fourier domain;

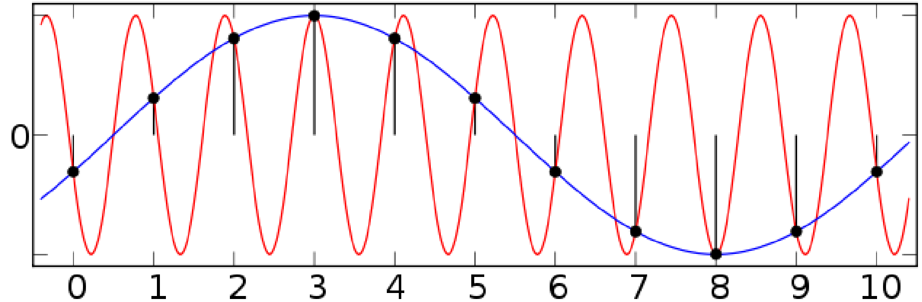
$\Rightarrow$ A periodic and discrete function has a periodic and discrete Fourier transform.



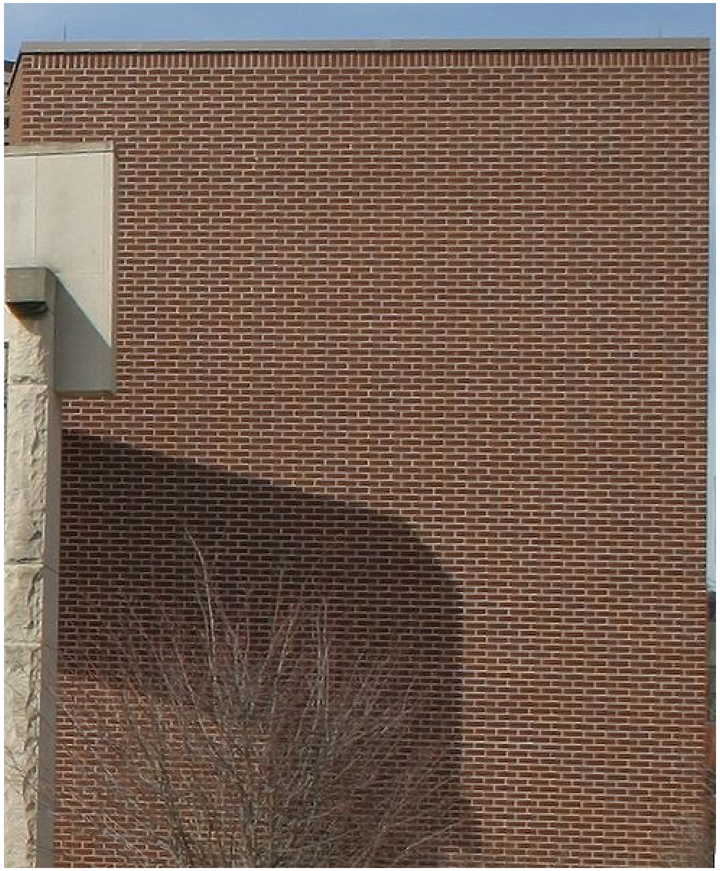


Aliasing

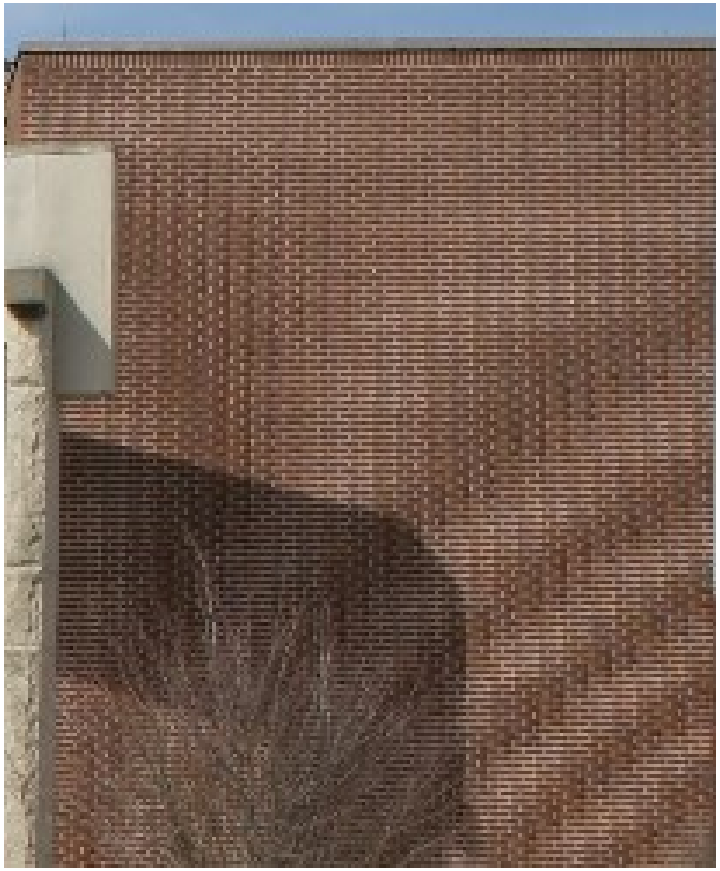
Moiré: after resampling, high spatial frequencies appear as low spatial frequencies



high resolution

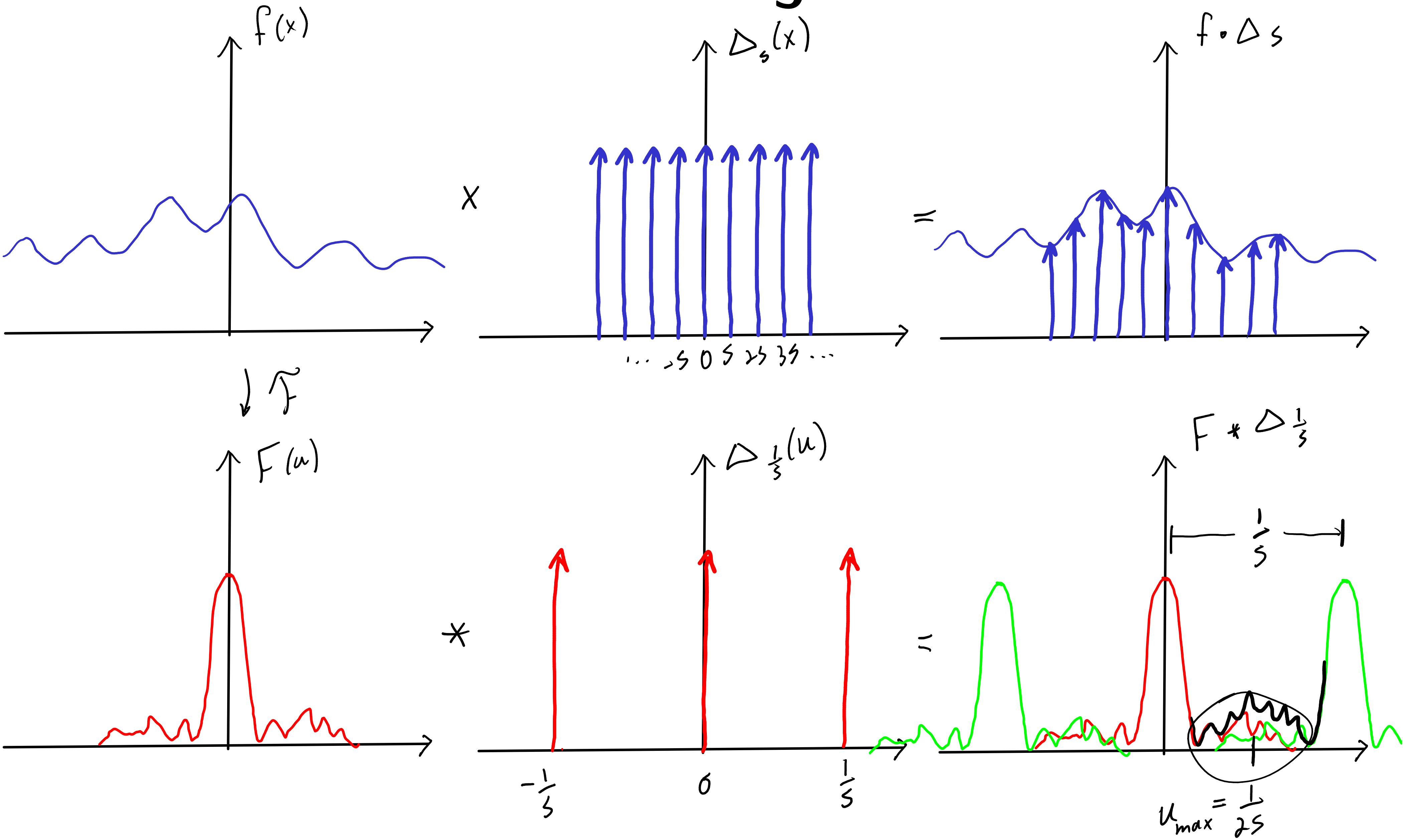


low resolution



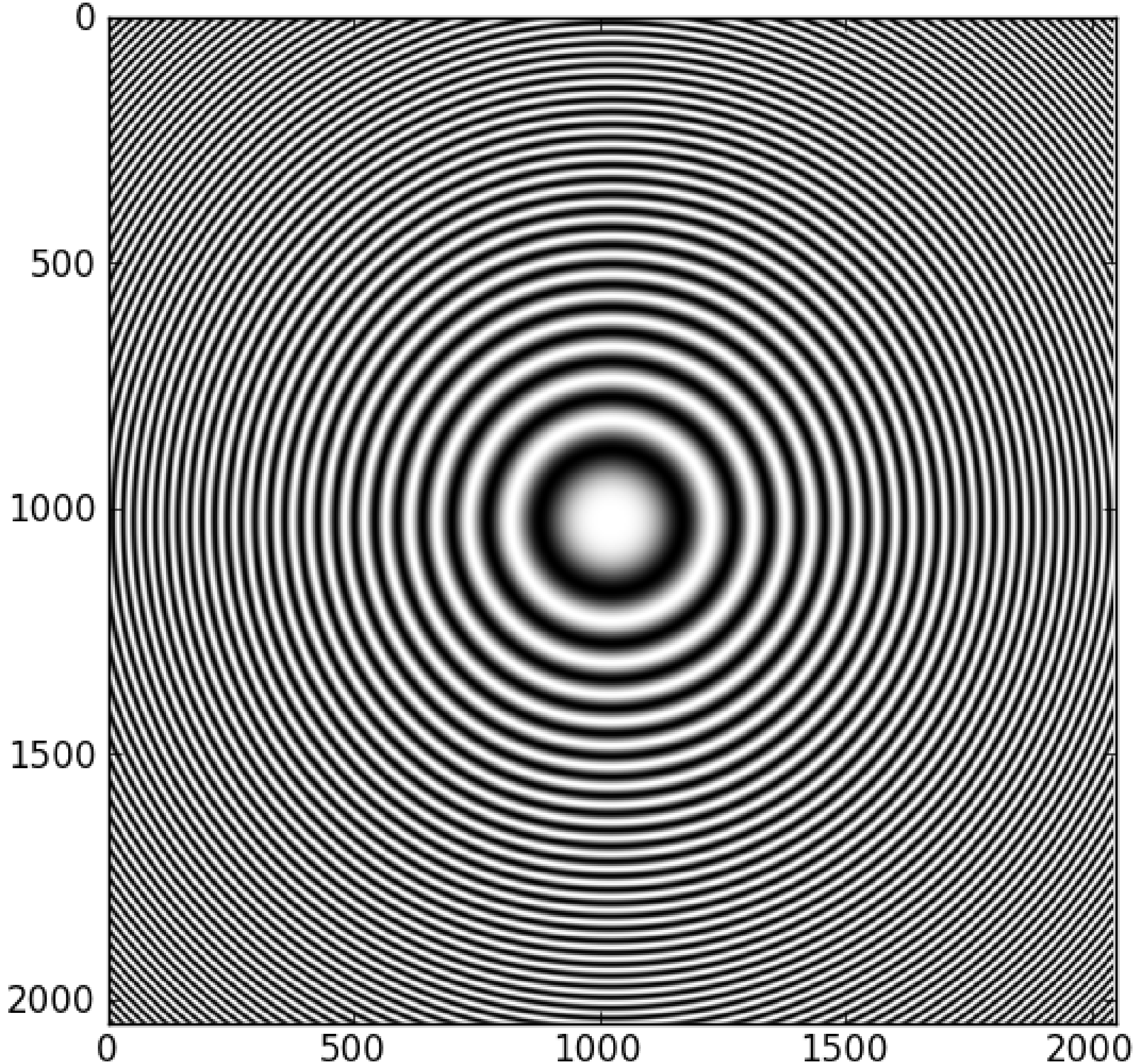
source: http://wikipedia.org

Aliasing



Undersampling

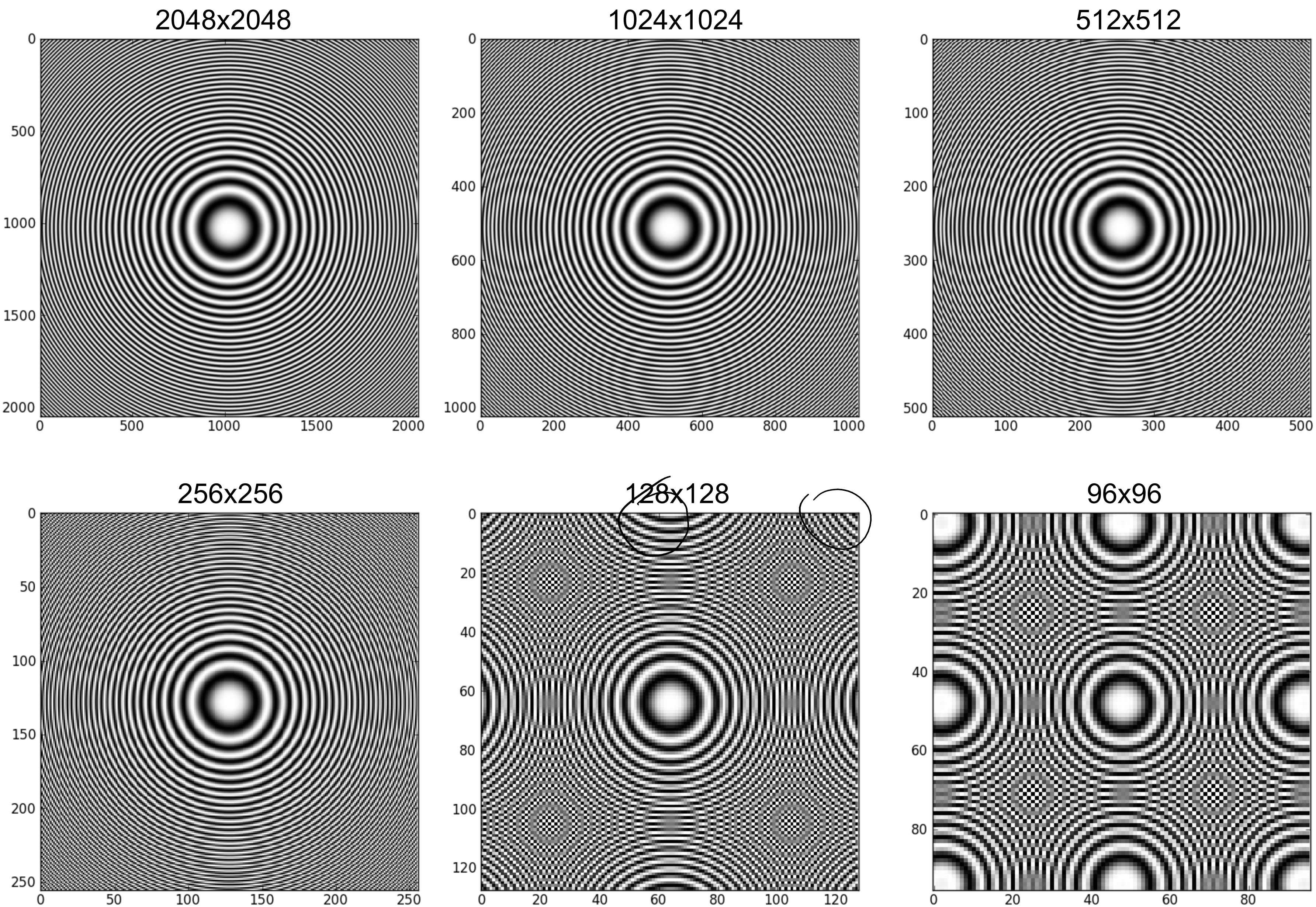
"Fresnel zone" test pattern: radial linear increase in spatial frequency



"radial chirp"

chirp: $\sin(ax^2)$

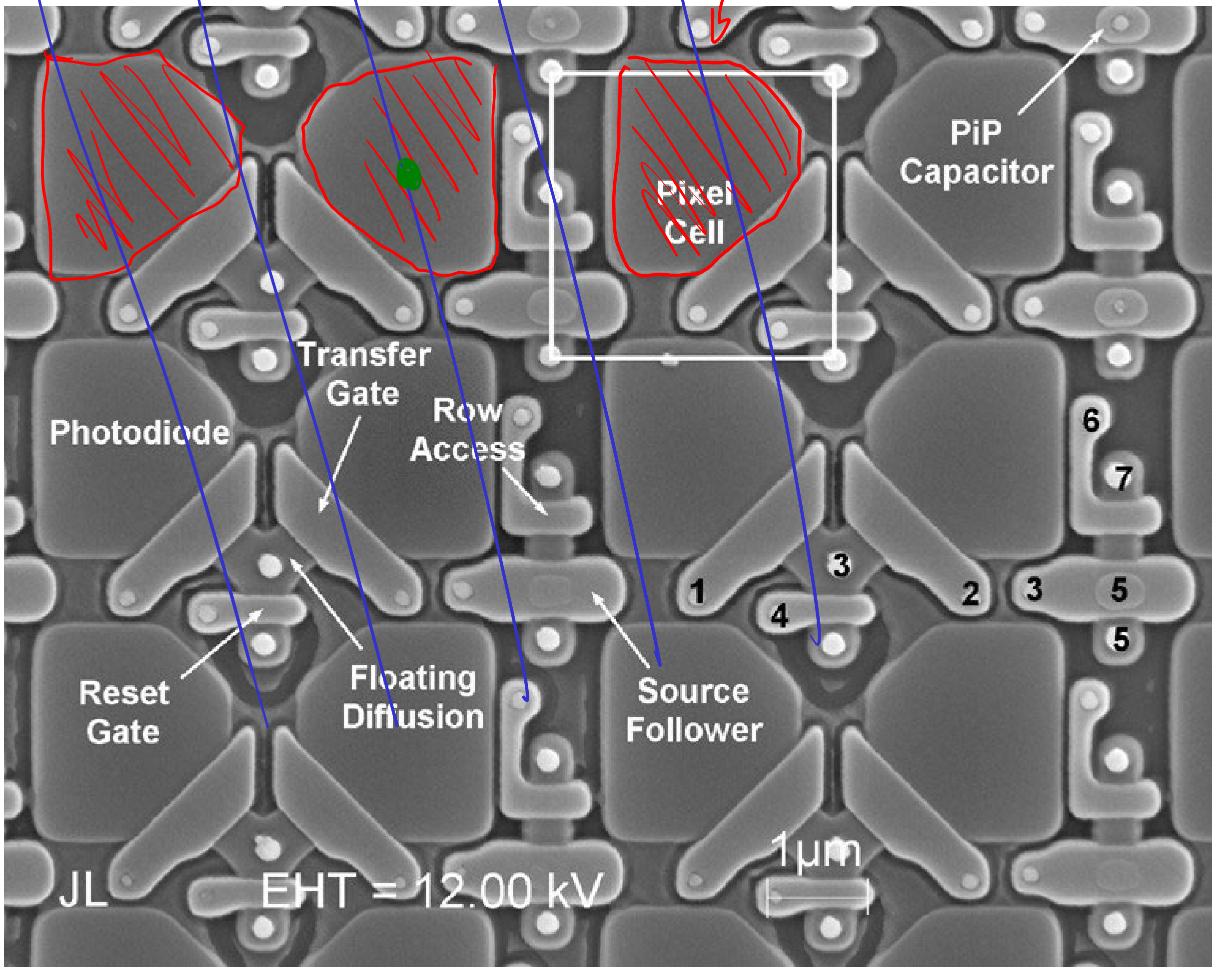
Undersampling & aliasing



Sampling with a pixel-array detector

- A 2D light field is sampled with a 2D pixel-array detector.

active area



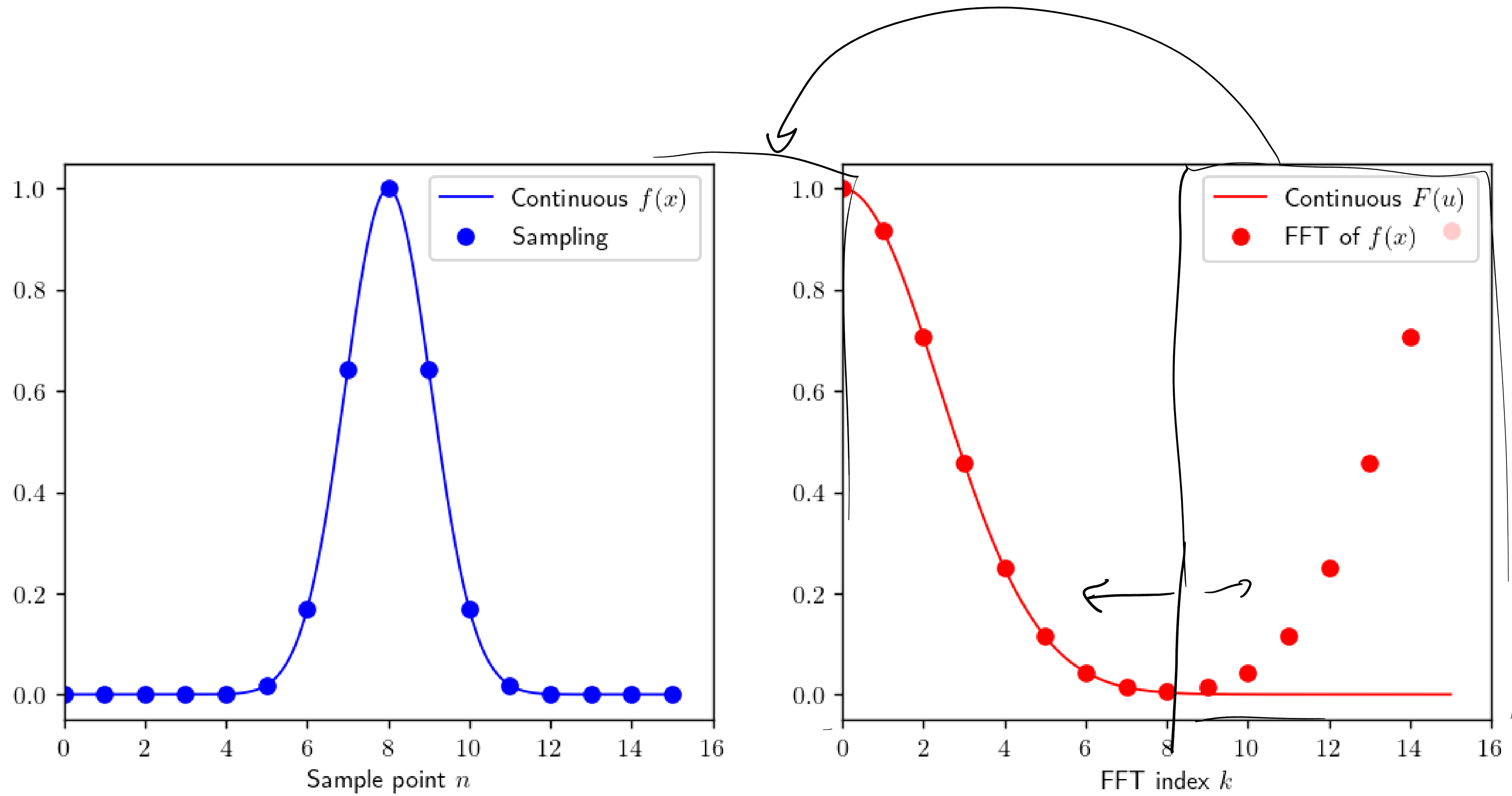
Discrete Fourier Transform

$$F_k = \sum_{n=\infty}^{N-1} f_n e^{-2\pi i kn/N}$$

- On computers, the signal is both sampled and of finite extent $\rightarrow$ using DFT on this signal means that is it assumed to be periodic.
- If the signal is sufficiently sampled, then the DFT can be interpreted as a sampled version of the continuous Fourier Transform.

DFT example

- Example: relation between space, sampling and frequency



zero frequency component is in the top left corner output array.

FT to DFT conversion

* look at the exp( ) argument

continuous: $e^{2\pi i u x}$

discrete: $e^{2\pi i n k / N}$

$$ux = \frac{nk}{N}$$

L = physical extent of f (period)

* function sampling $f(x) \to f_n$

step size $s \Rightarrow x = ns$

$$u = \frac{k}{Ns} = \frac{k}{L}$$

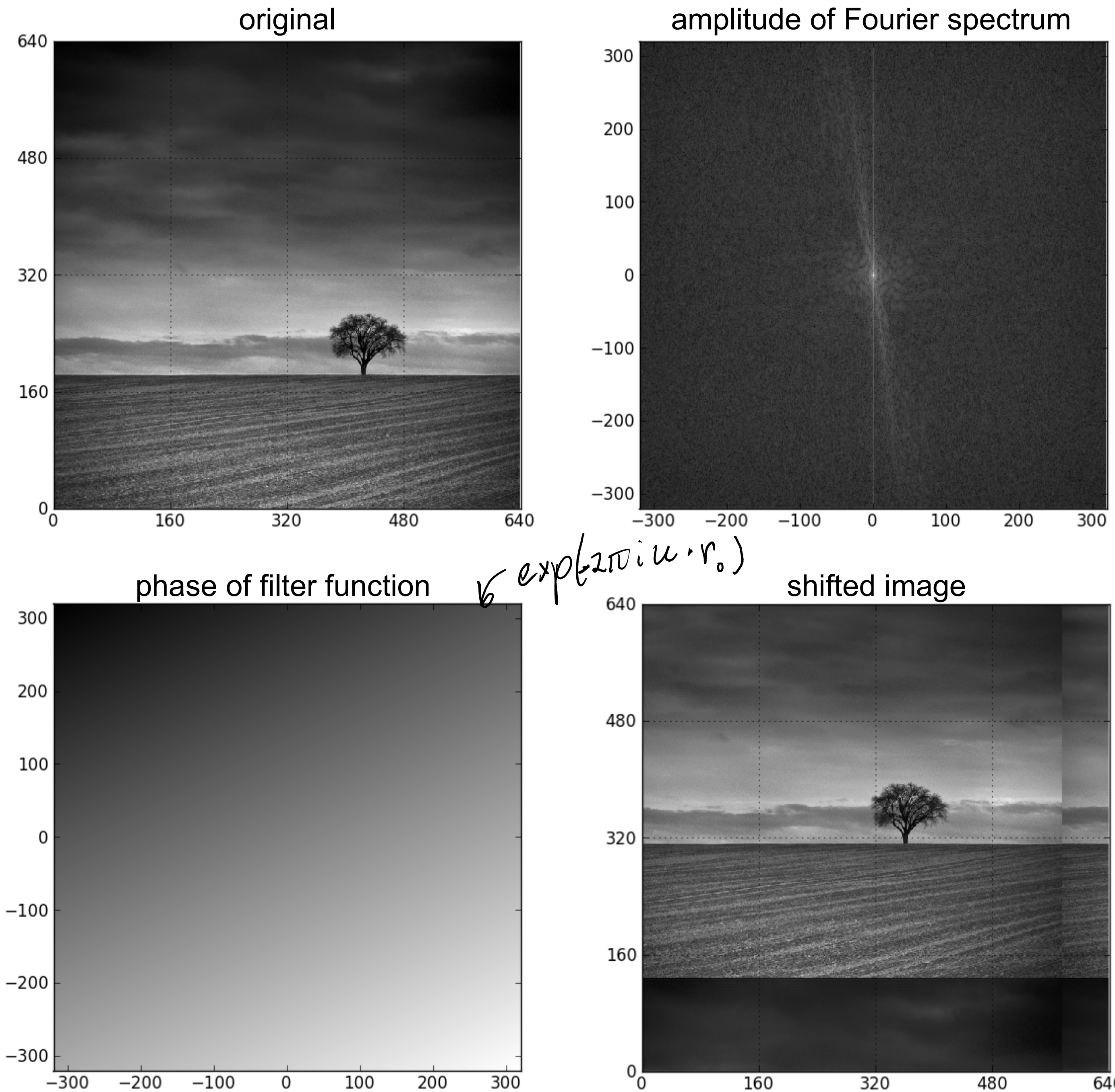
Observation

$$F_{k+N} = \sum_{n=0}^{N-1} f_n e^{-2\pi i n (k+N)/N}$$

$$= \sum_{n=0}^{N-1} f_n e^{-2\pi i n \frac{k}{N}} \overbrace{e^{-2\pi i n}}^{1} = F_k$$

F_k is periodic

Fourier space translation

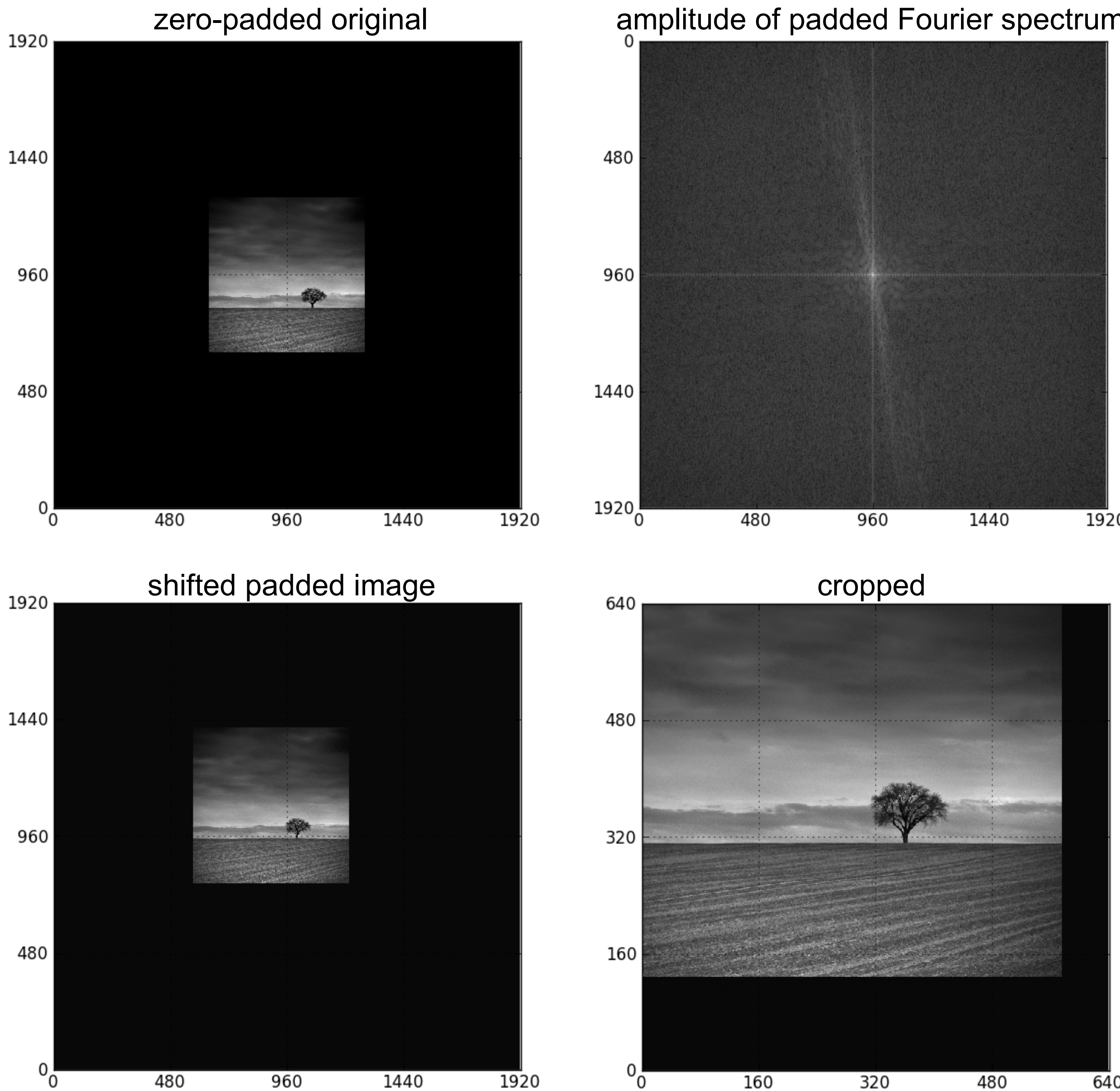


$\exp(-2\pi i\, u \cdot r_0)$

Image shifting using shifting property of FT

Image gets wrapped around

Zero-padding

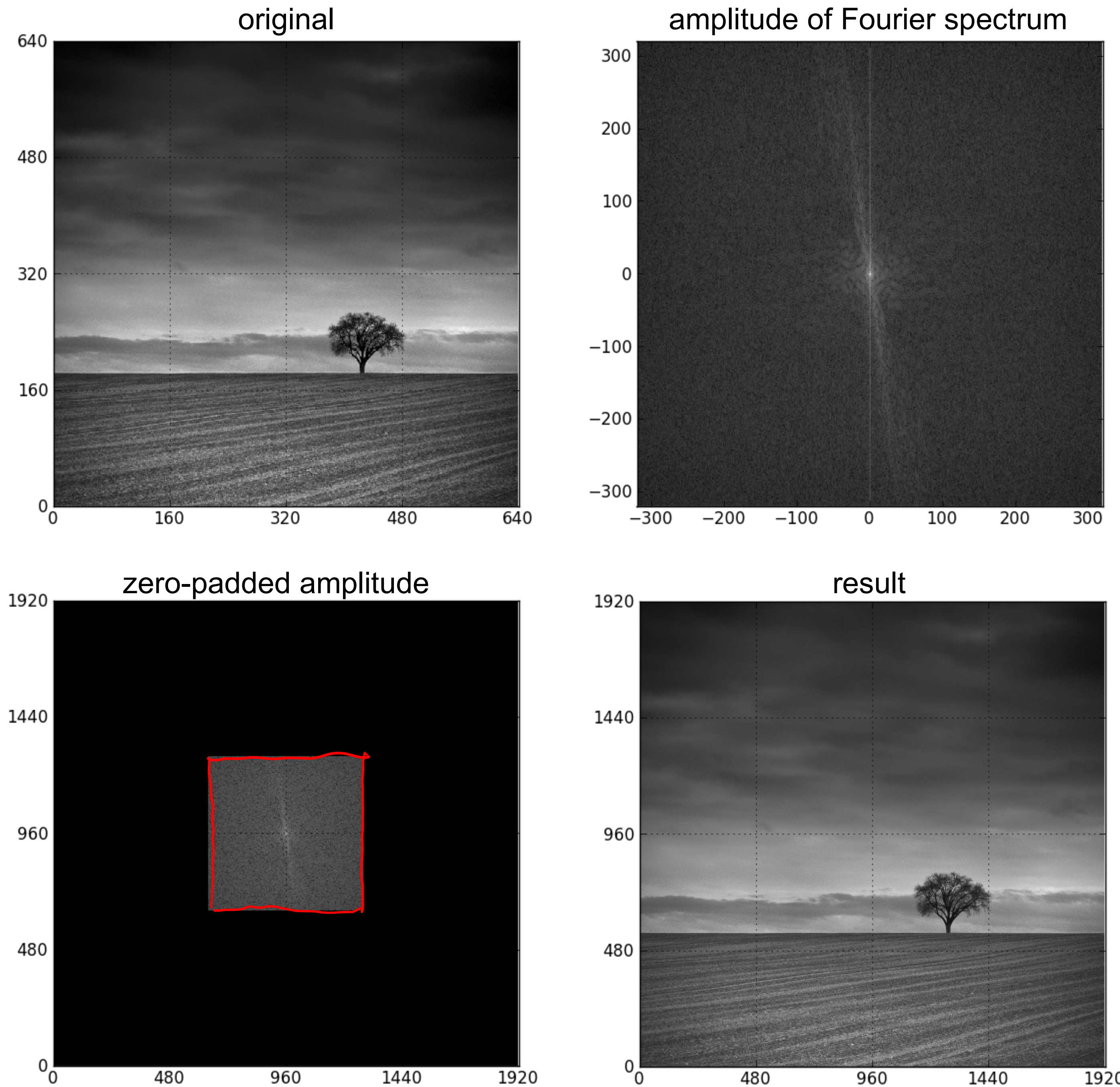


1. Add zeros around original image (*zero-padding*)

2. Shift using FT

3. Crop result

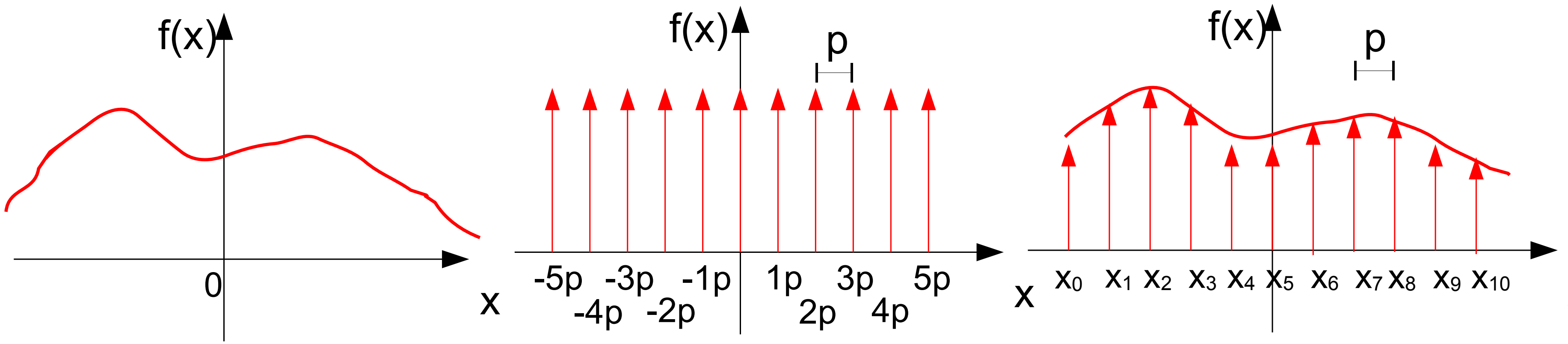
Zero-padding in Fourier space



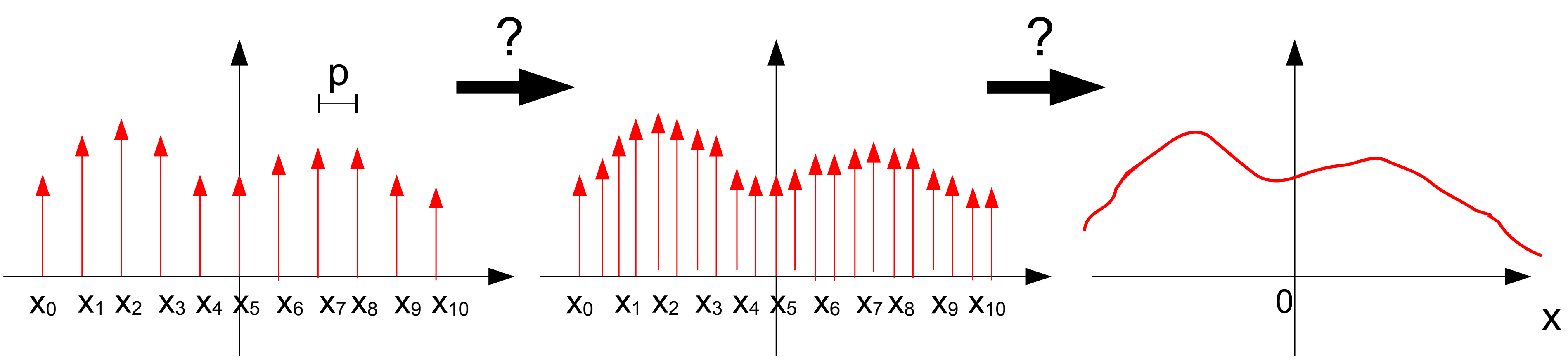
Result: increased sampling!

Interpolation

- Discrete sampling of a continuous function



- Reconstruct original function from sampled data?

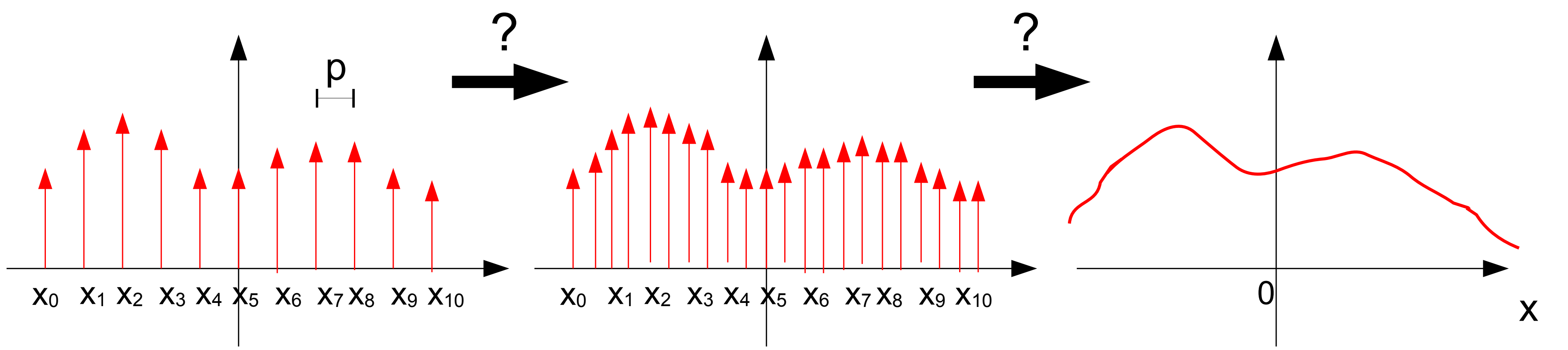


Interpolation

Finding unknown points between known ones

- wide field, many different approaches
- closely related to approximation theory and curve fitting

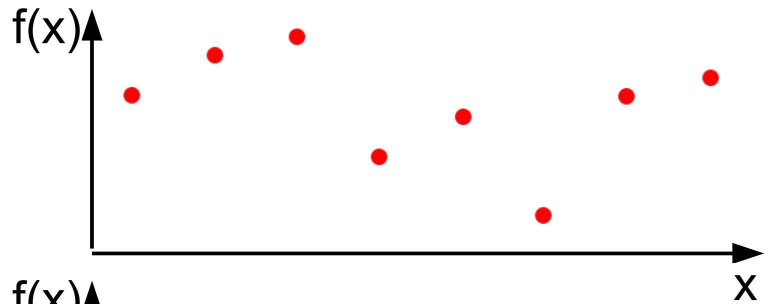
difference : interpolated curve has to pass through all known samples



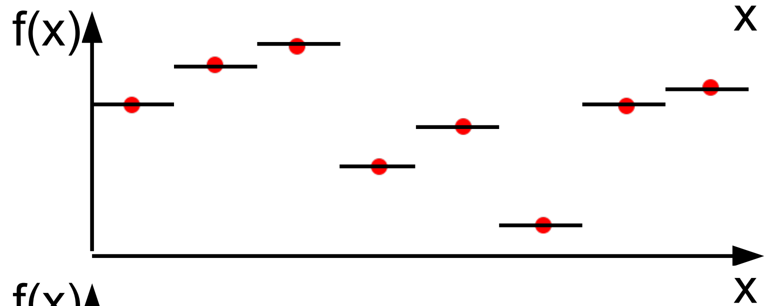
Interpolation

Various "classical" interpolation methods available

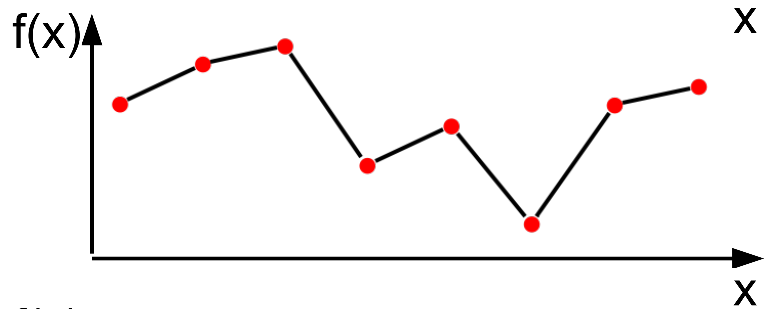
sampled points



nearest neighbor



linear



cubic spline

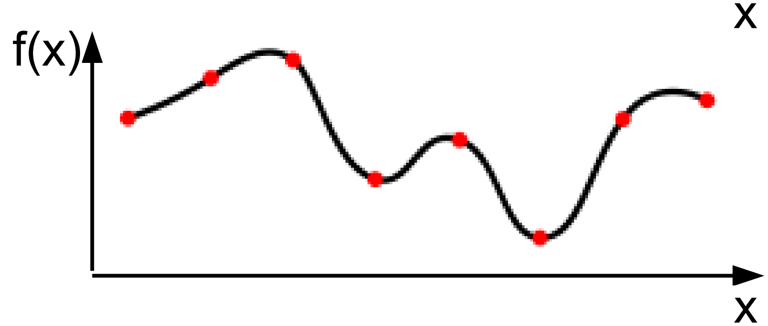
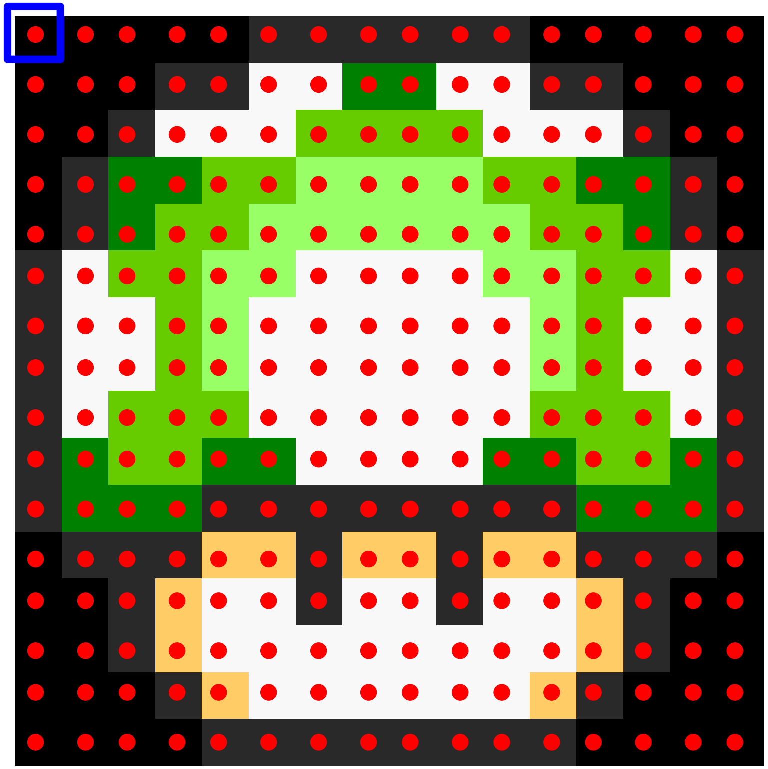


Image pixels

Images are discrete samples of a continuous function

- ...with coordinates
- ...and values (voltage at coordinate, integral over pixel area, ...)
- ...represented by <u>pixel basis functions</u> on a <u>sampling grid</u>



Linear interpolation

space of continuous functions

$$\mathcal{L} : \mathbb{R}^N \to C_0$$

- Interpolation as an operator

$$f(x) = \mathcal{L}\{f_n\}$$

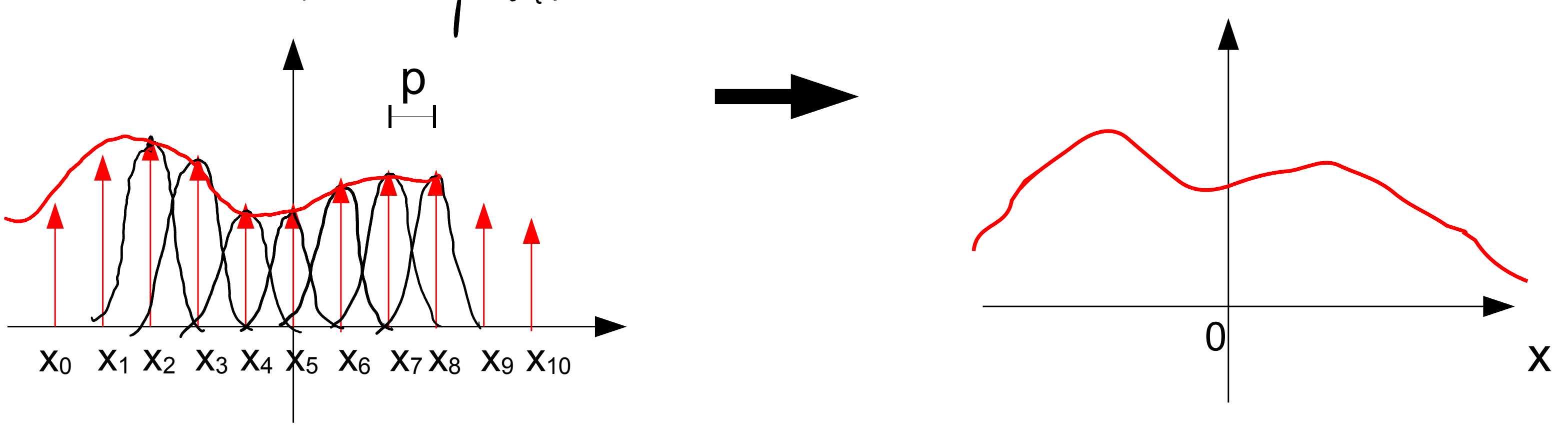
- Linear interpolation

$$\mathcal{L}\{f_n + g_n\} = \mathcal{L}\{f_n\} + \mathcal{L}\{g_n\}$$

- Shift invariance

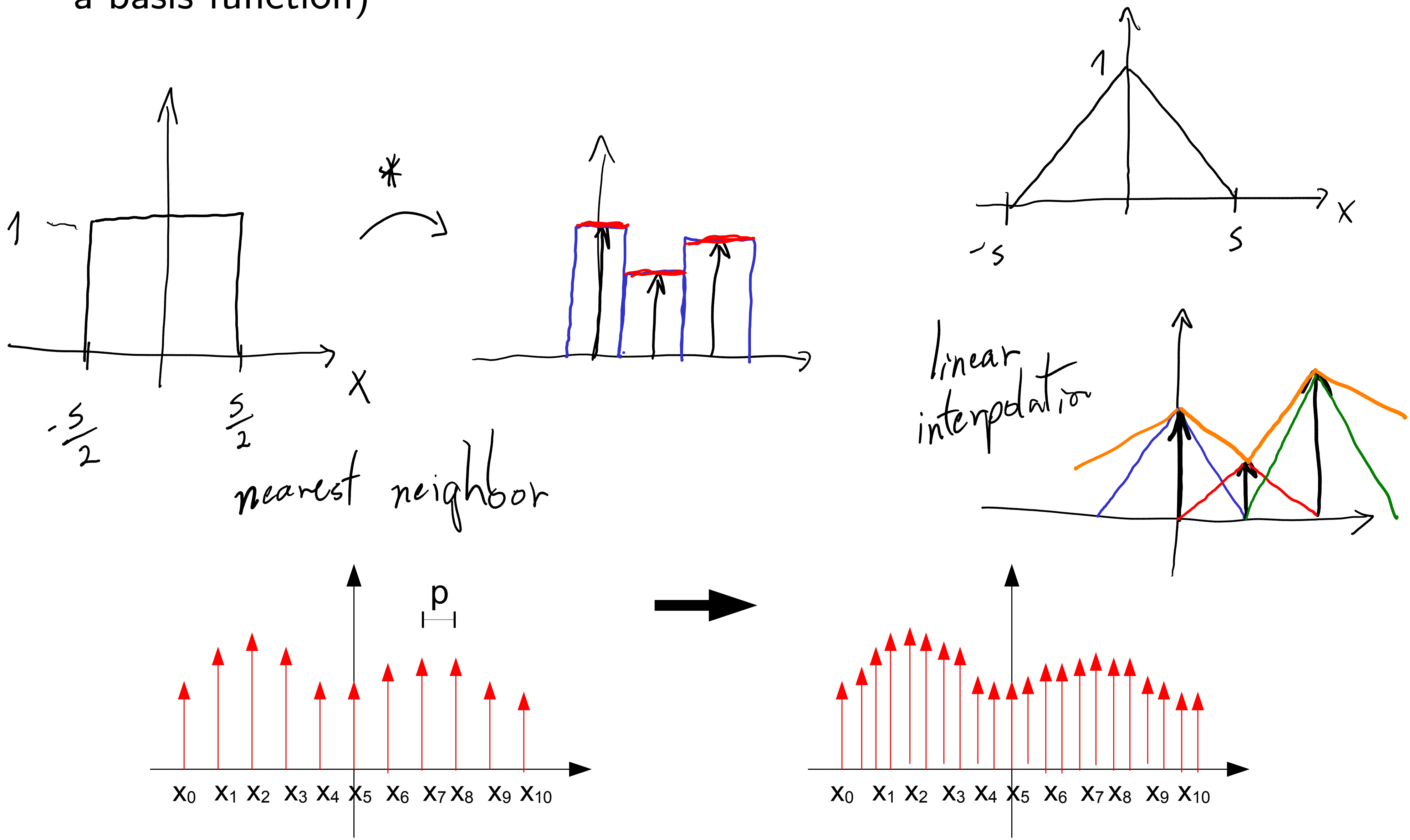
$$\mathcal{L}\{f_{n+n_0}\} = f(x + n_0 s)$$

- Kernel → interpretation as a convolution



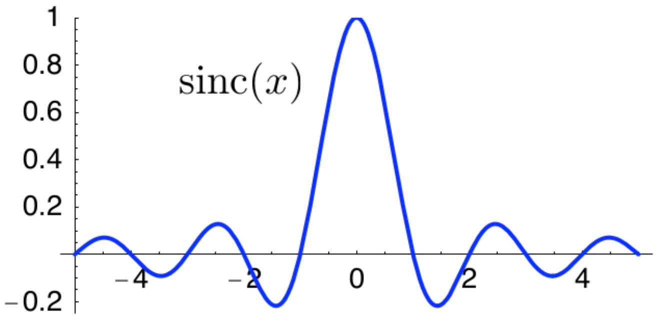
"Linear interpolation"

- Linear interpolation can be written as a convolution with a kernel (e.g. a basis function)

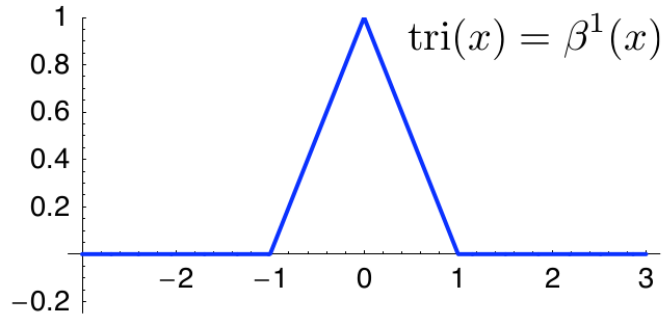


Linear interpolation

- Bandlimited



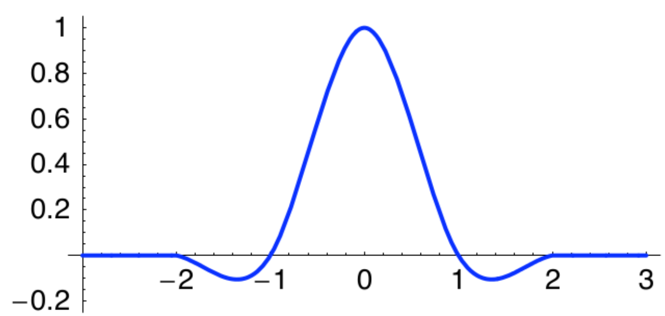
- Piecewise linear



Interpolation condition:

$$\varphi_{\mathrm{int}}(k) = \delta_k = \begin{cases} 1, & k = 0 \\ 0, & \text{otherwise} \end{cases}$$

- Cubic convolution

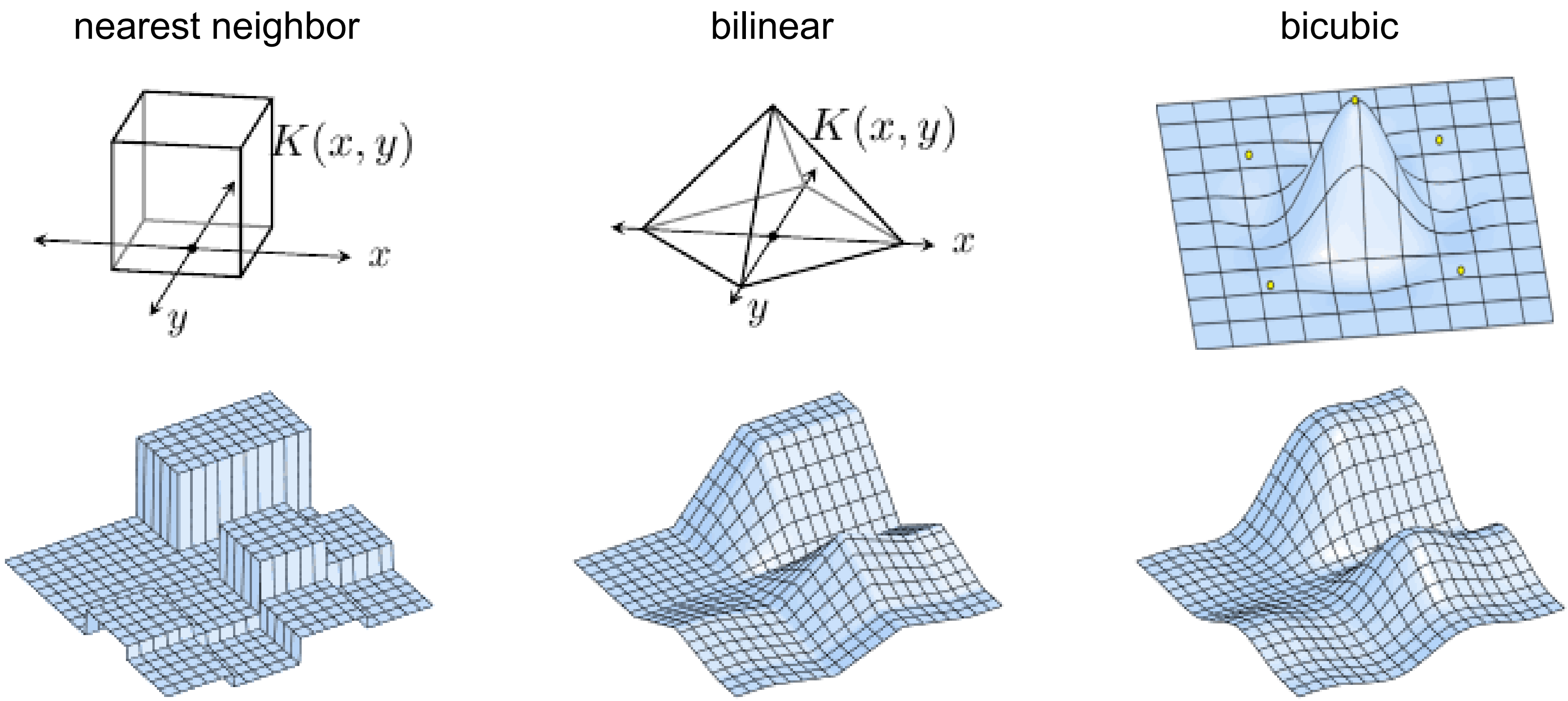


[Keys, 1981; Karup-King 1899]

source: http://bigwww.epfl.ch/tutorials/unser_isbi_06_part1

2D interpolation

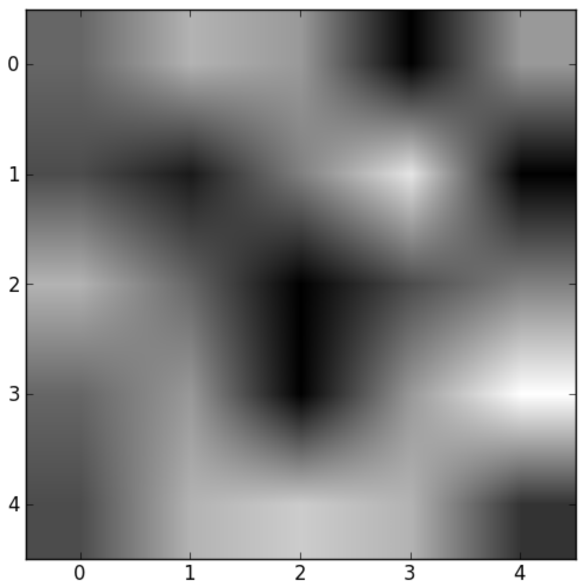
- Make 2D interpolation linear in each variable



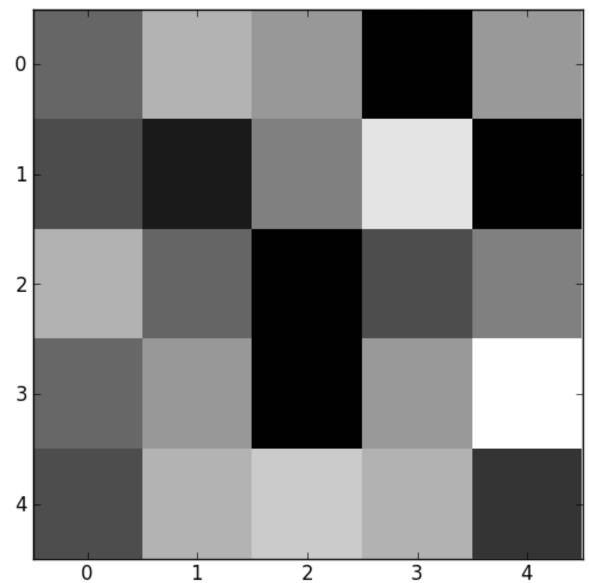
source: http://www.ipol.im/pub/art/2011/g_lmii/

Python plotting

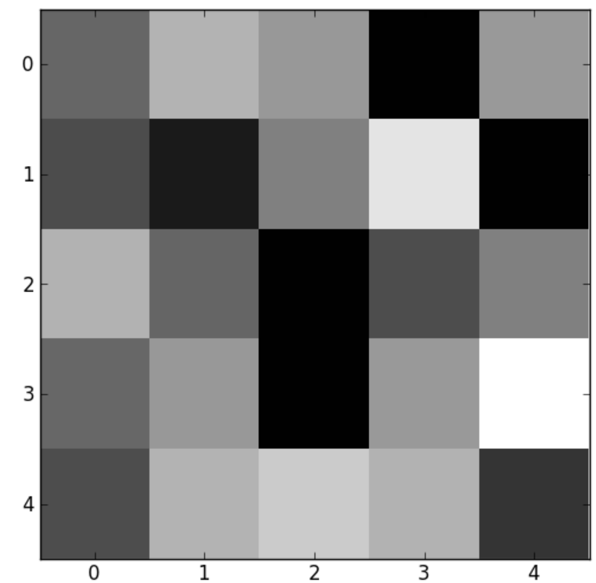
plt.imshow(im)



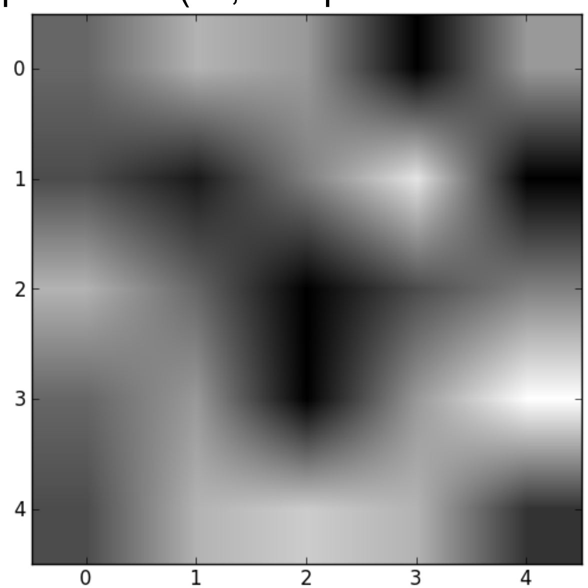
plt.imshow(im, interpolation='none')



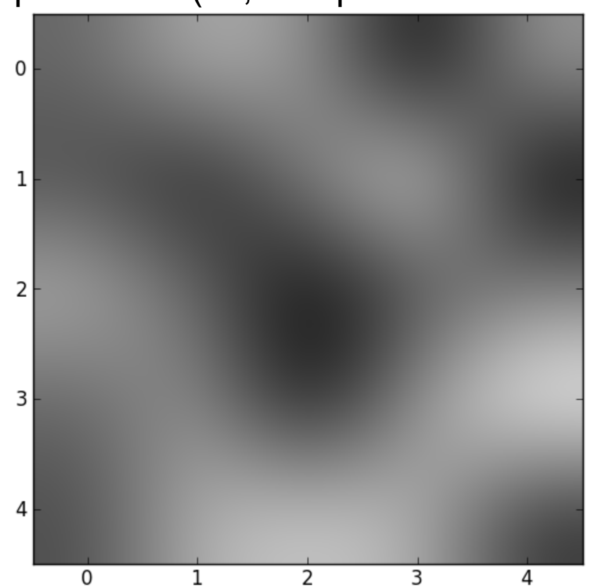
plt.imshow(im, interpolation='nearest')



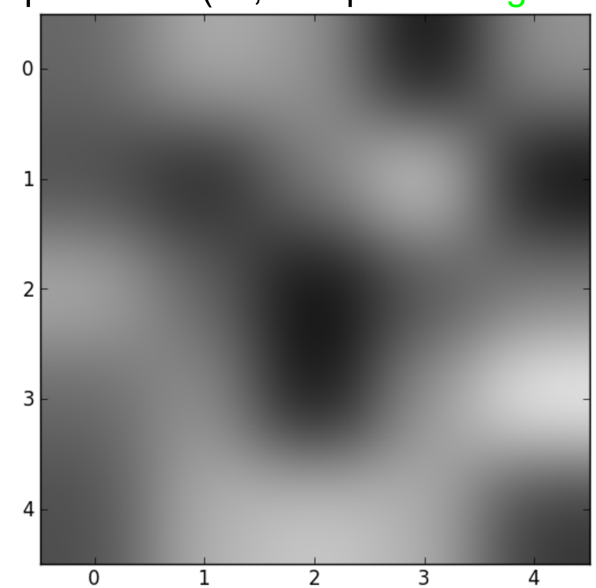
plt.imshow(im, interpolation='bilinear')



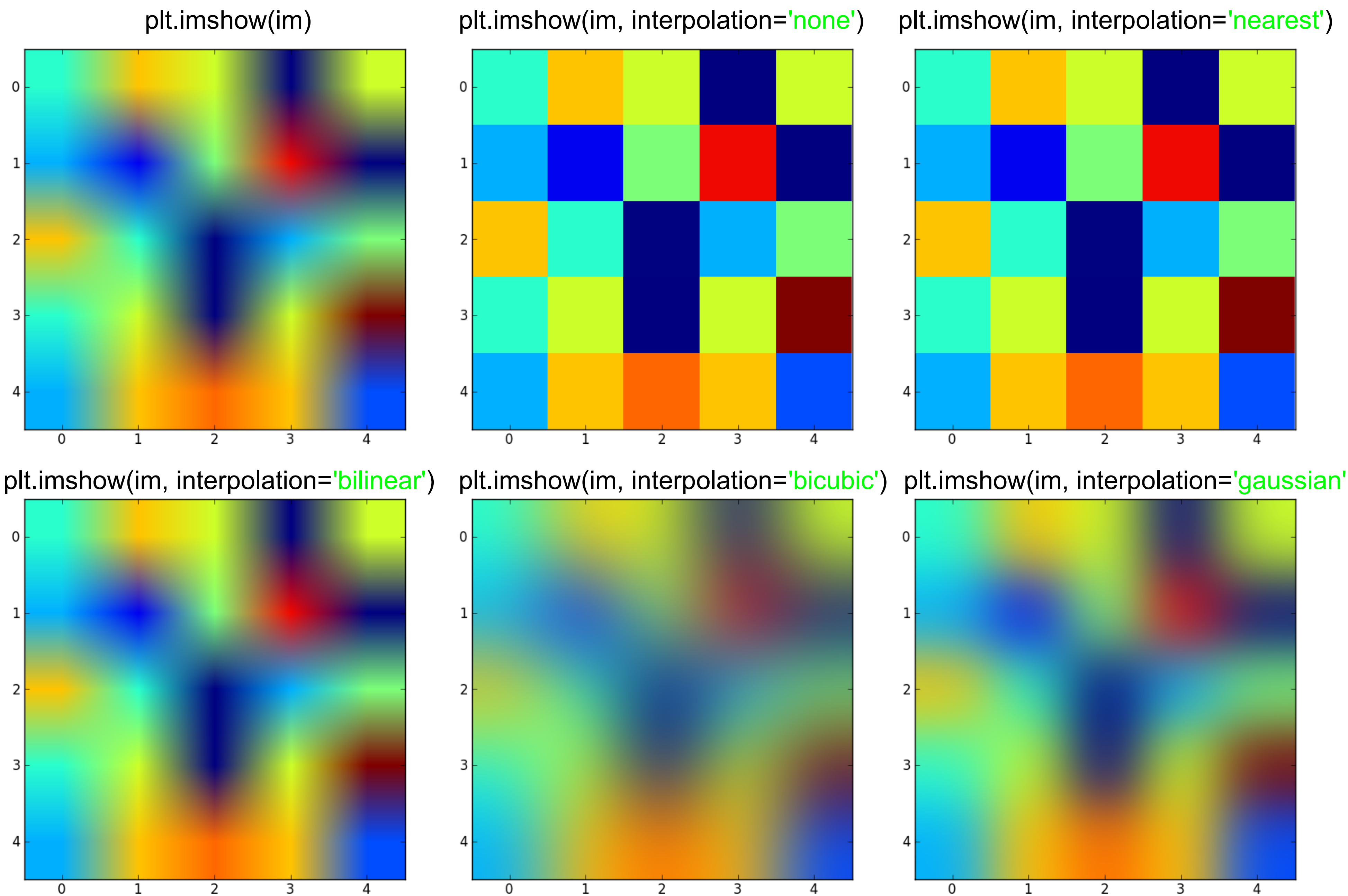
plt.imshow(im, interpolation='bicubic')



plt.imshow(im, interpolation='gaussian')

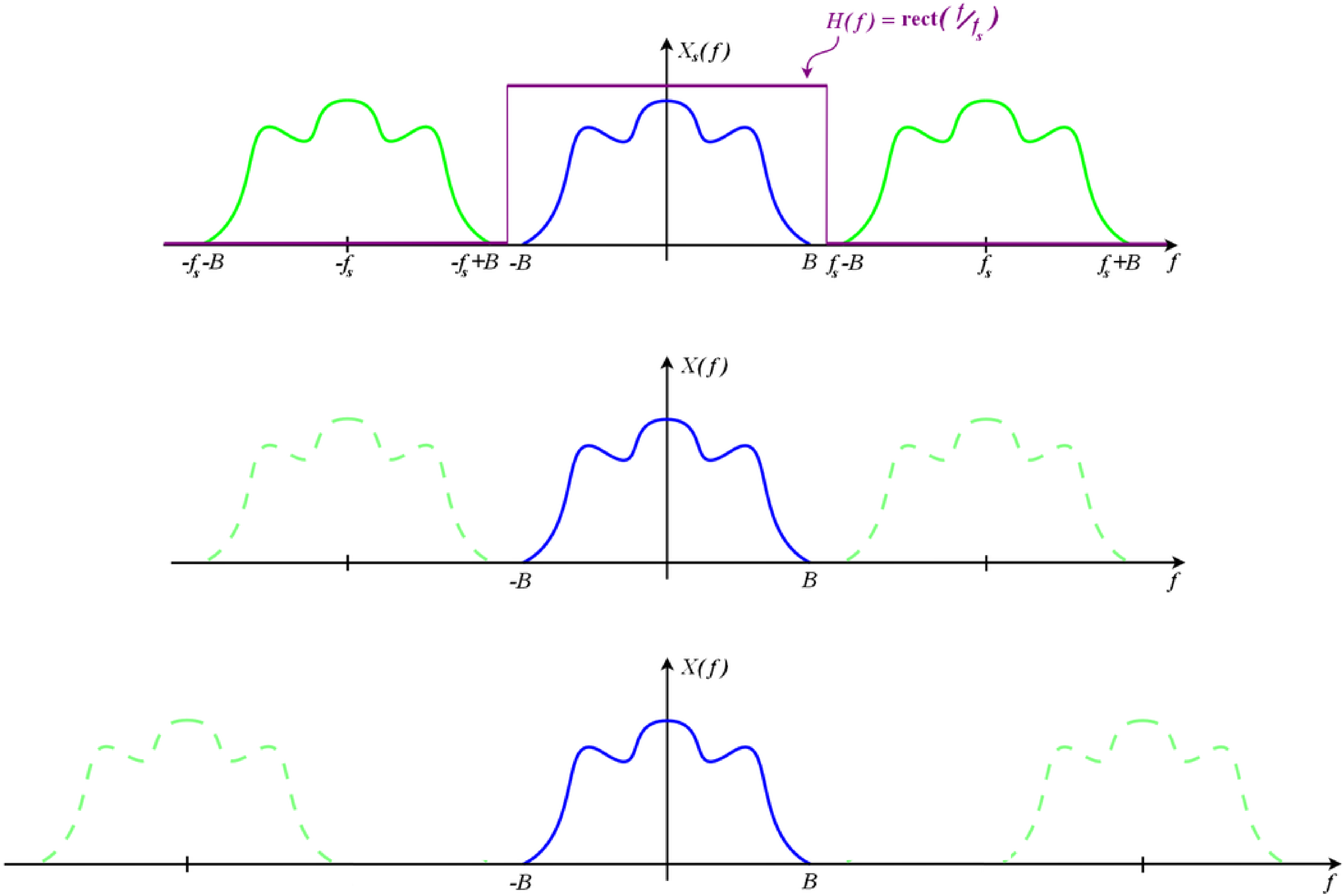


Python plotting



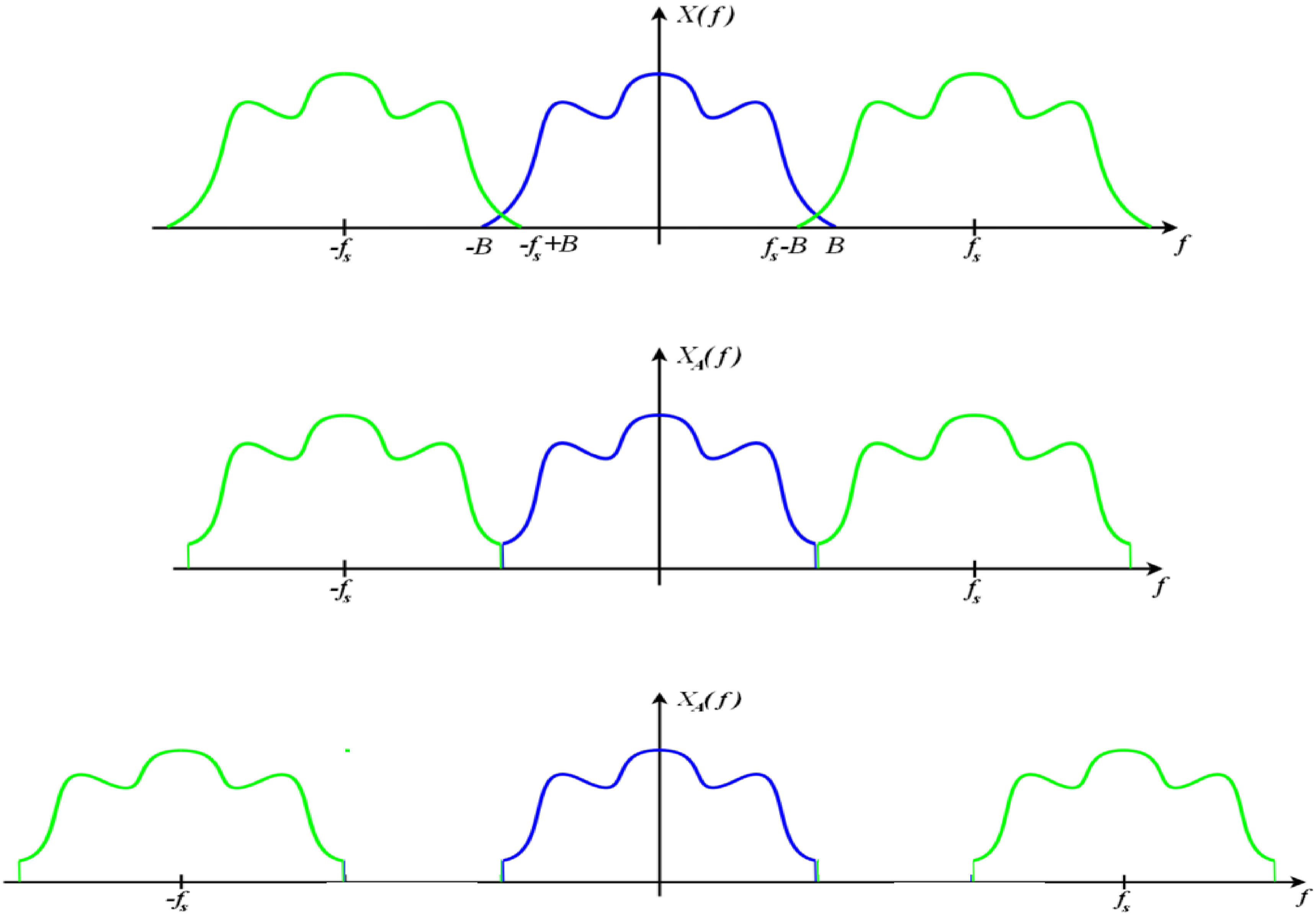
Sinc interpolation and zero-padding

Also known as "Whittaker–Shannon interpolation"



Sinc interpolation and zero-padding

Also known as "Whittaker–Shannon interpolation"

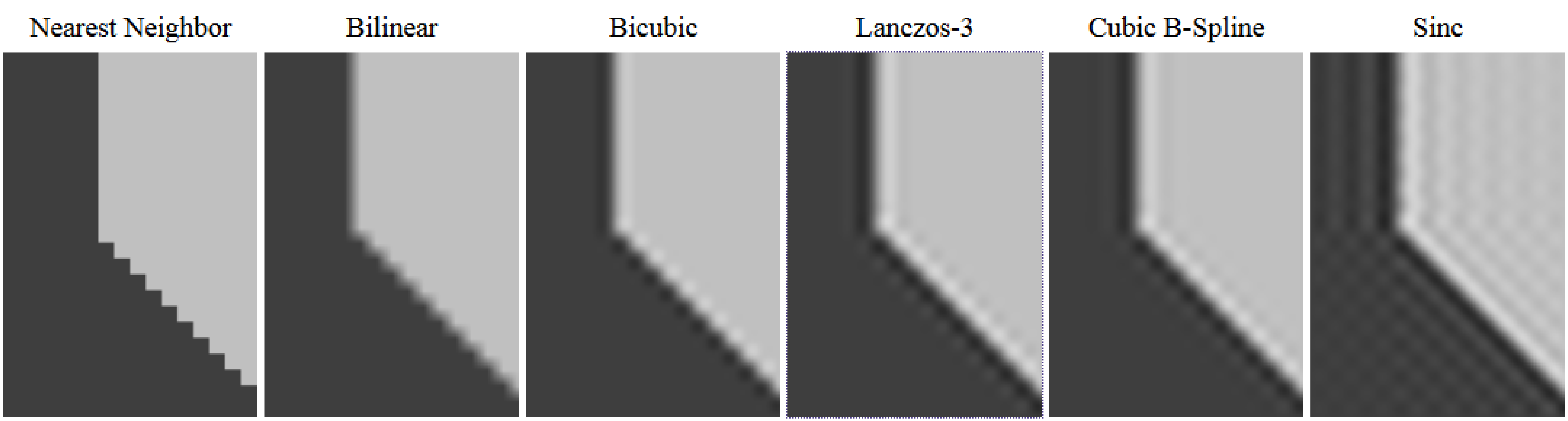


Reconstruction from samples

- Sinc interpolation can perfectly reconstruct a function from its samples if
  - sampled at a rate higher than Nyquist rate
  - bandlimited up to Nyquist frequency
  - no aliasing

equivalent

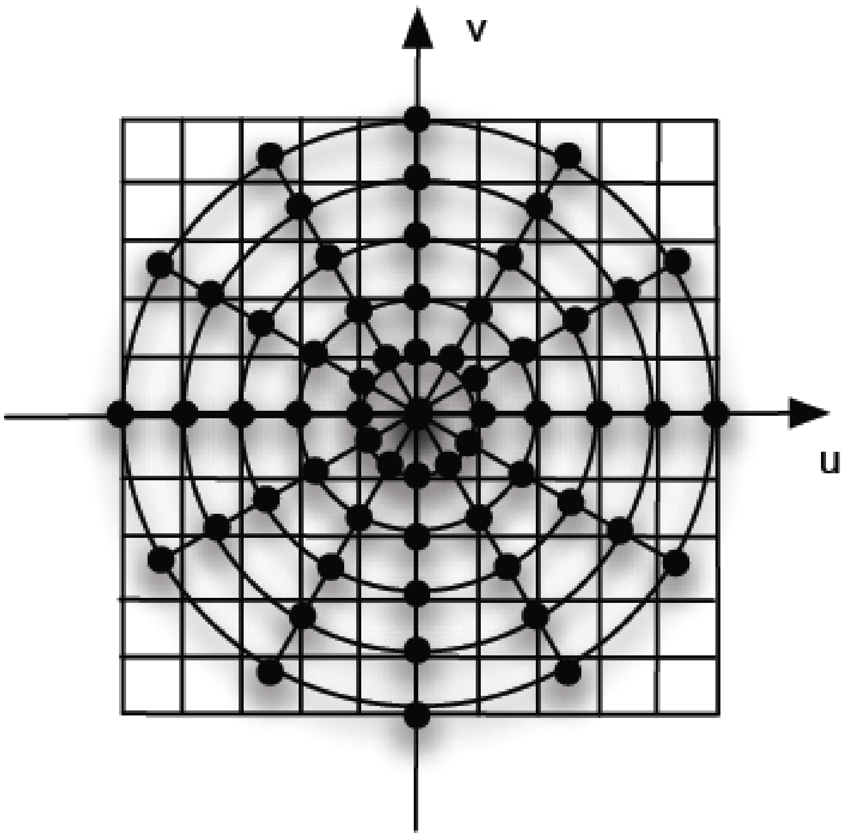
- Sinc interpolation introduces ringing otherwise, due to leakage of aliased frequencies



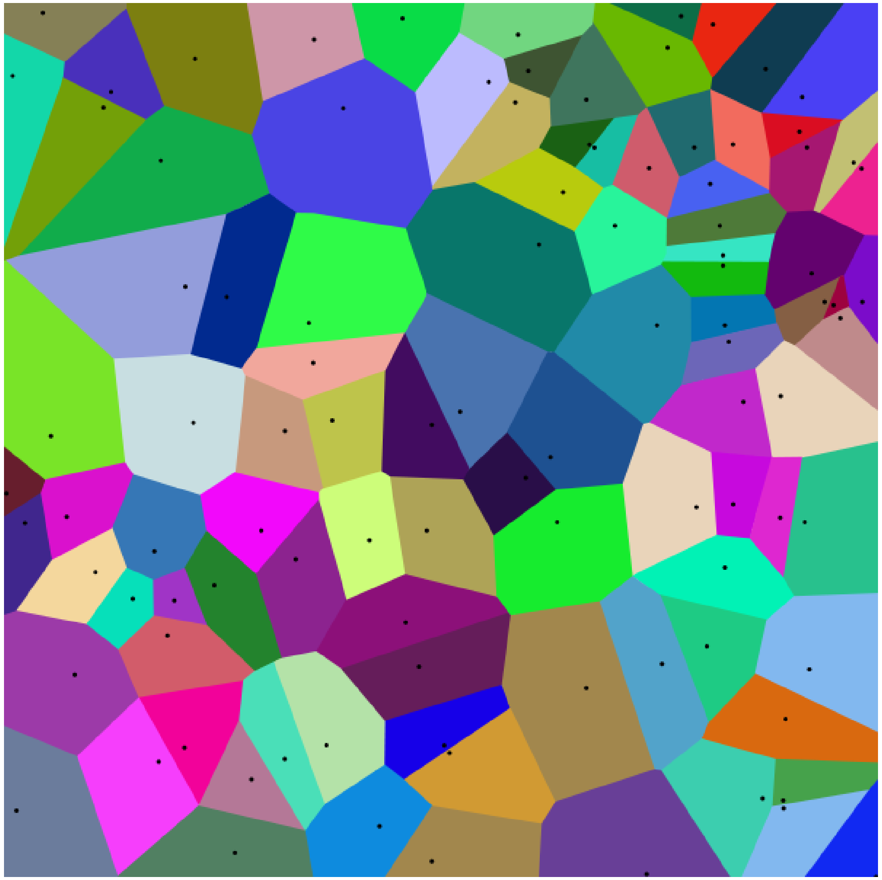
Linear interpolation of a step edge: a balance between staircase artifacts and ripples.

Other Interpolation

- Change from polar to cartesian grid
- Linear, but not translation invariant



polar vs. cartesian sampling



irregular sampling

Example: log-polar coordinates

Summary

- Images can be represented as a sampling grid and pixel basis functions
- Need for interpolation arises when changing the grid
- Linear and translation invariant interpolation can be written as a convolution with an interpolation kernel function
- Typical interpolation kernels include nearest neighbor, linear, cubic and higher B-spline interpolation
- Zero-padding in one domain equals sinc interpolation in the other
- “ideal” sinc interpolation may lead to ringing artifacts