

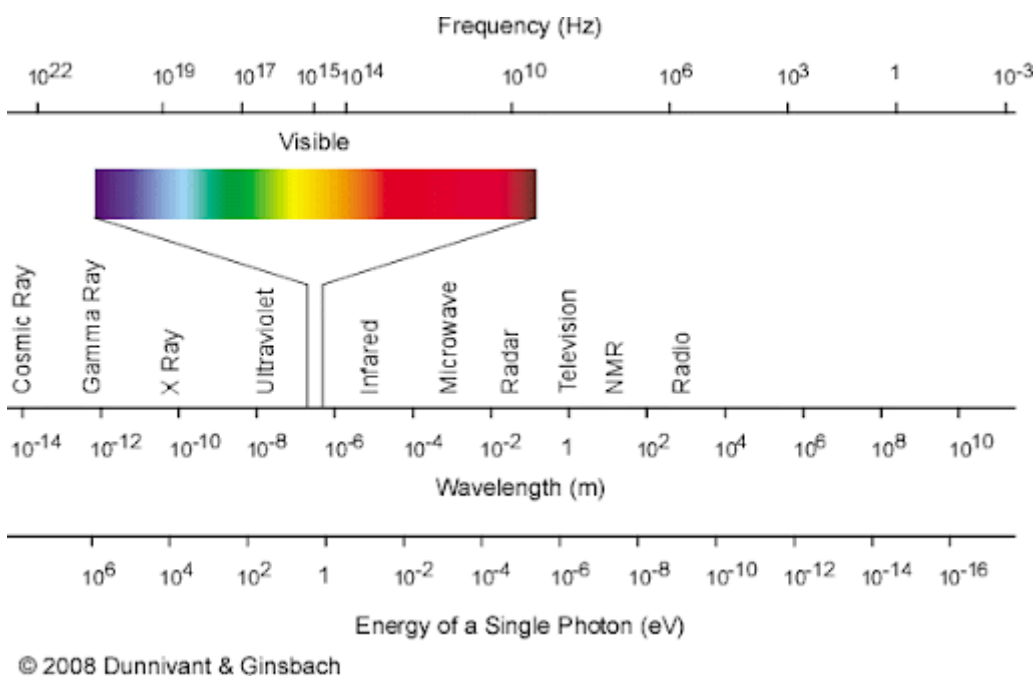
# Optics

## Properties of light

### Wave particle duality:

Light is a wave

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## Absorption and Emission

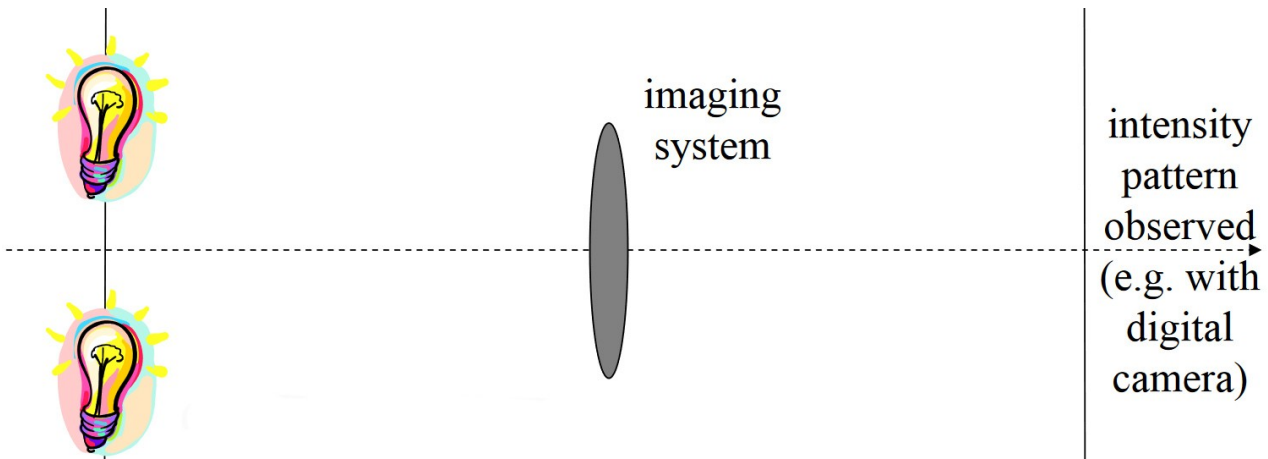
Beer's law

Refraction

# Ray tracing

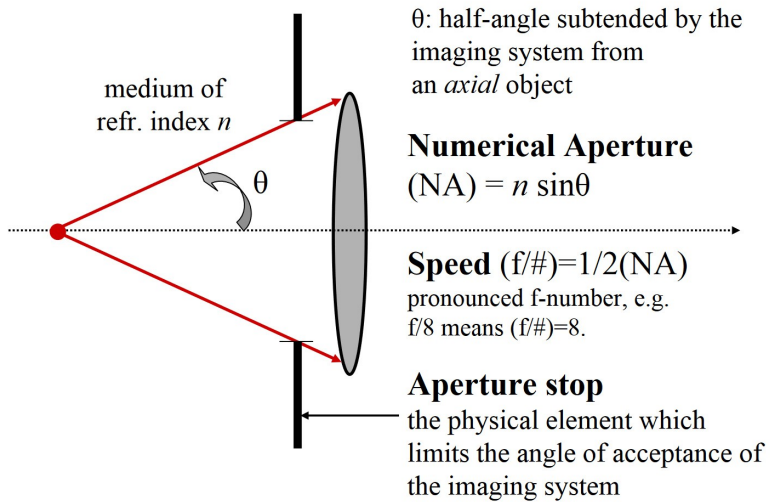
## Resolution

**Resolution:** The ability to separate two objects



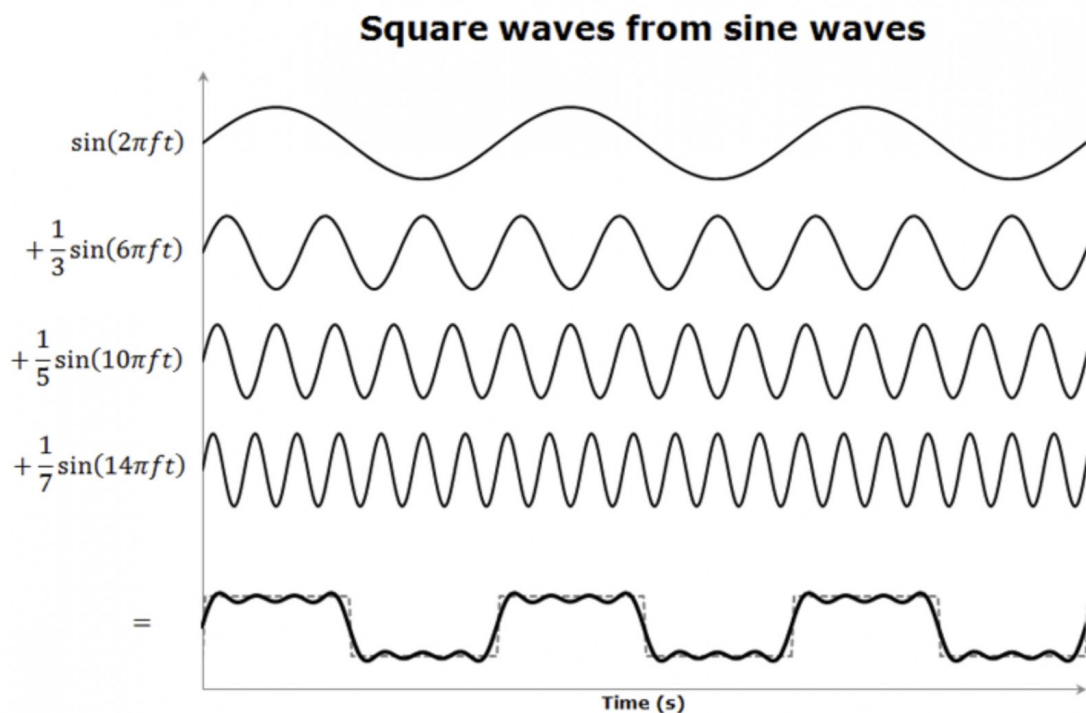
## A definition of Numerical Aperture

## Numerical Aperture and Speed (or F-Number)



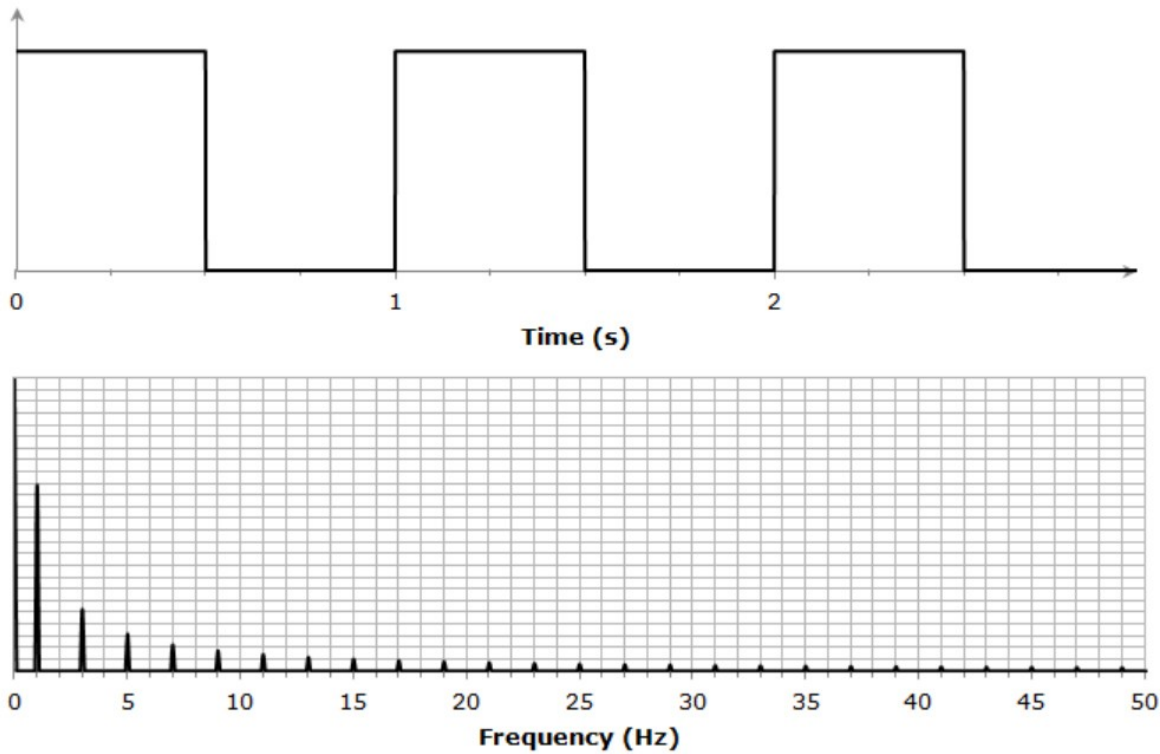
## Fourier transform:

Transform from real space to frequency space



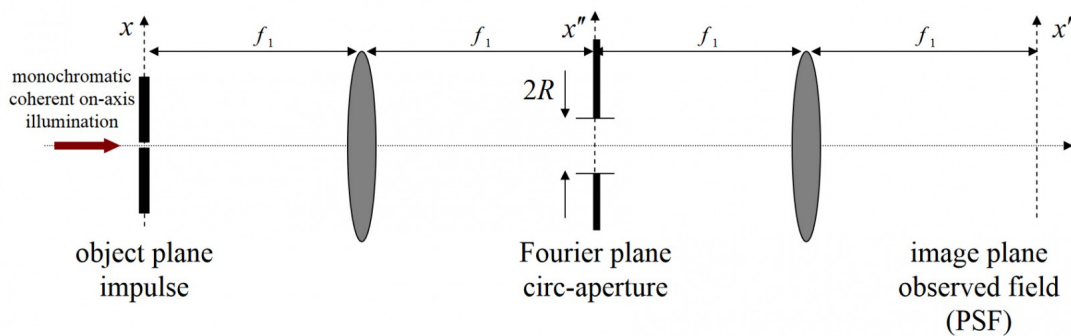
Now we look at a real square wave and frequency space

## 1 Hz square wave



## Look at a simple optical system:

### PSF vs NA



## Mathematical prediction of the Point Spread Function (PSF)

on the left we have the mathematical point source know as a delta function.

$$g_{\text{in}}(x, y) = \delta(x)\delta(y)$$

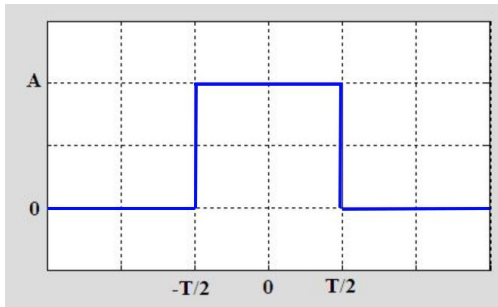
were

$$\delta(x) = \begin{cases} 0, & x \neq 0, \\ \infty, & x = 0, \end{cases}$$

the intensity at the Fourier plain can be found by taking the Fourier transform of this function.

$$F(\omega) = \mathcal{F}(\delta(x)) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \delta(x) e^{i\omega x} dx = \frac{1}{2\pi}.$$

or

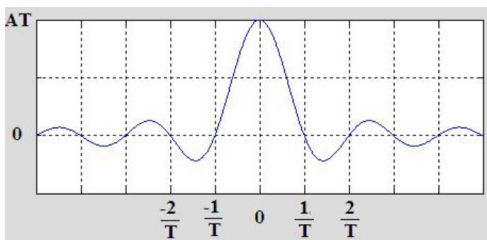


this has the same intensity at all points inside the aperture and zero outside. The second lens is now taking a Fourier transform on a box function the width of the aperture.

$$\text{jinc}(\cdot, \cdot) \equiv 2 \frac{J_1\left(2\pi \frac{R}{f_1} \frac{r'}{\lambda}\right)}{2\pi \frac{R}{f_1} \frac{r'}{\lambda}}$$

(unit magnification)

or

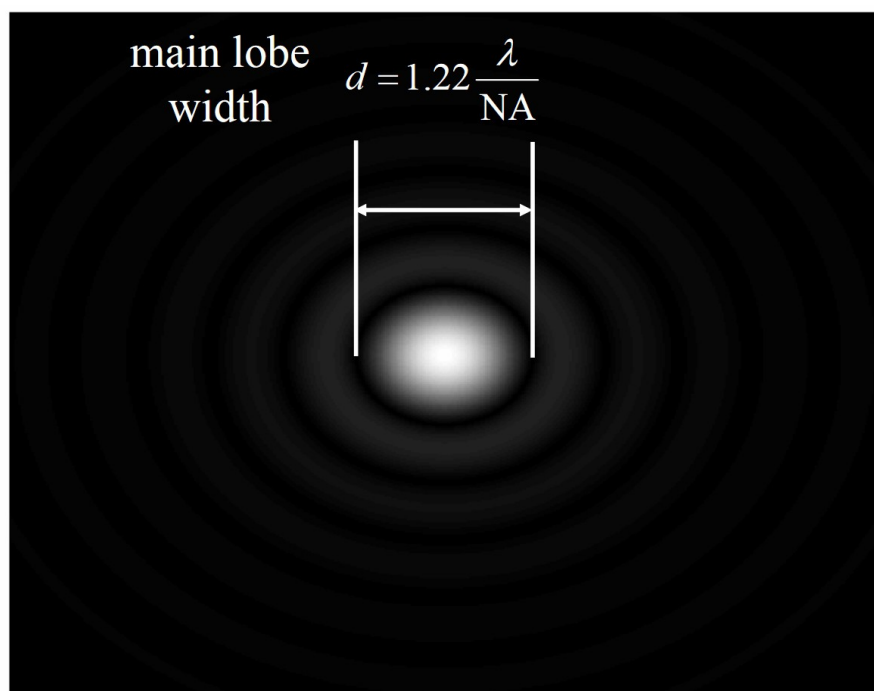
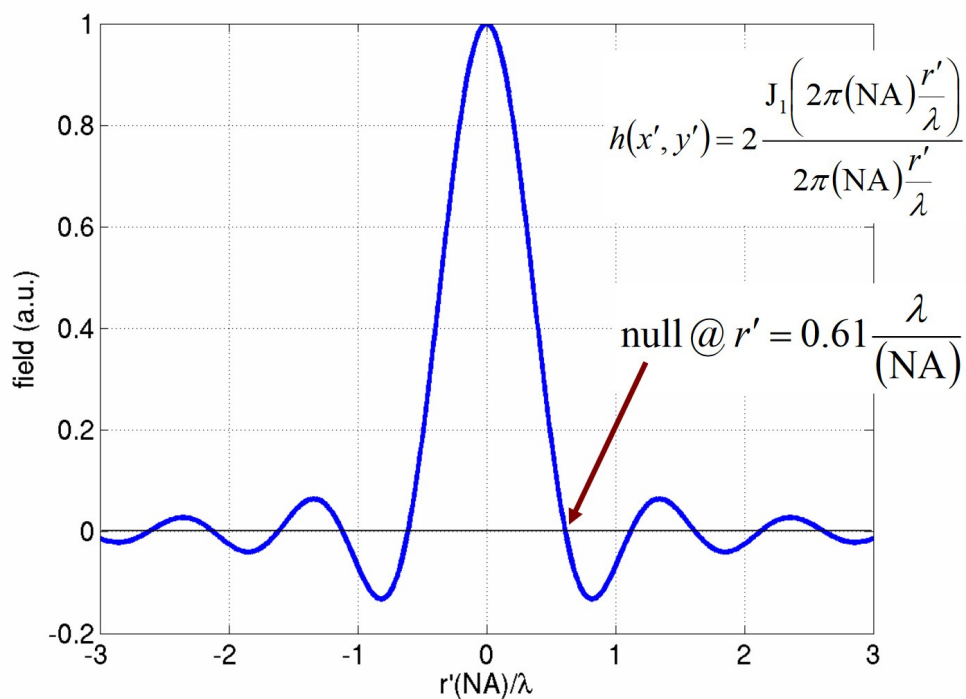


Substituting in the definition for NA

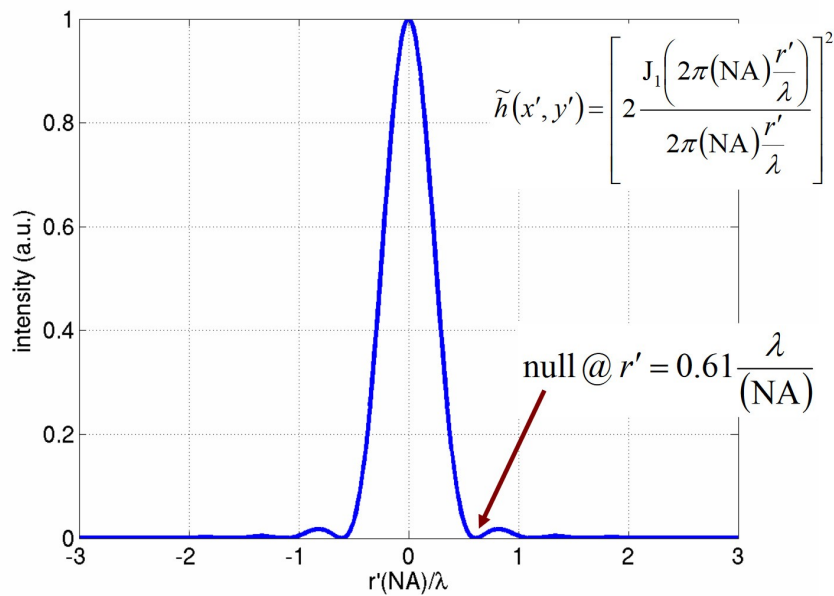
Numerical Aperture (NA) by definition:

$$(NA) \equiv \frac{R}{f_1}$$

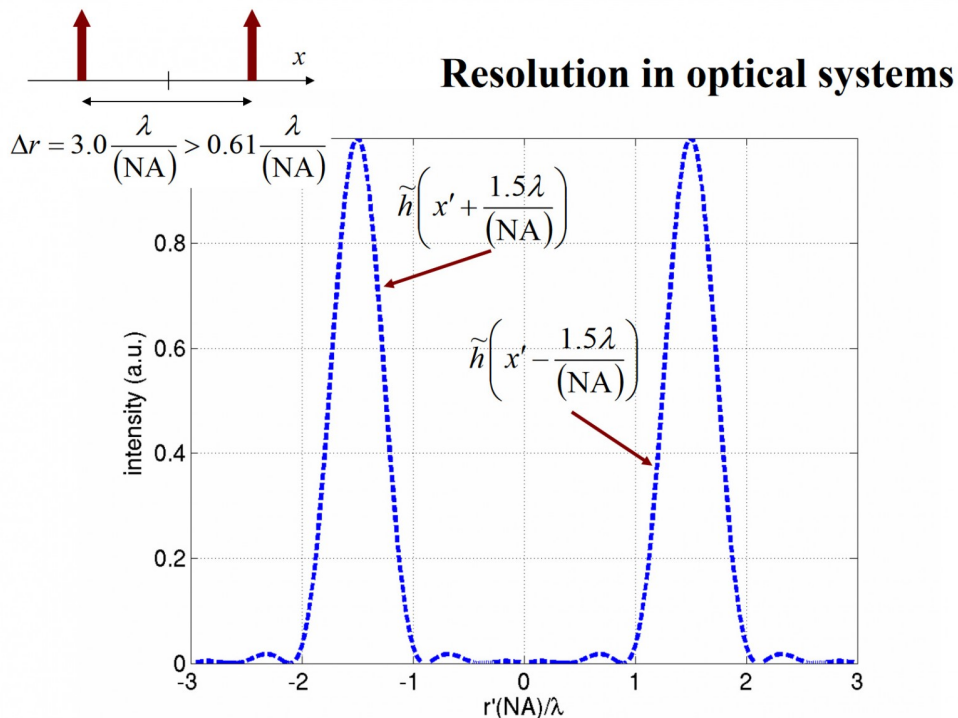
# PSF *vs* NA

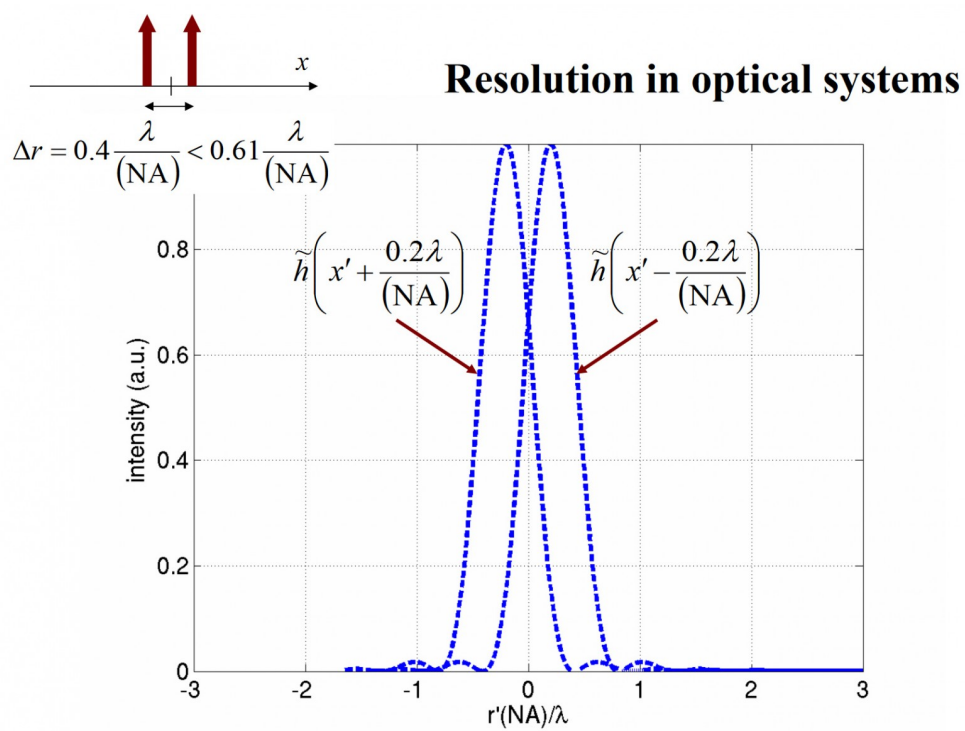
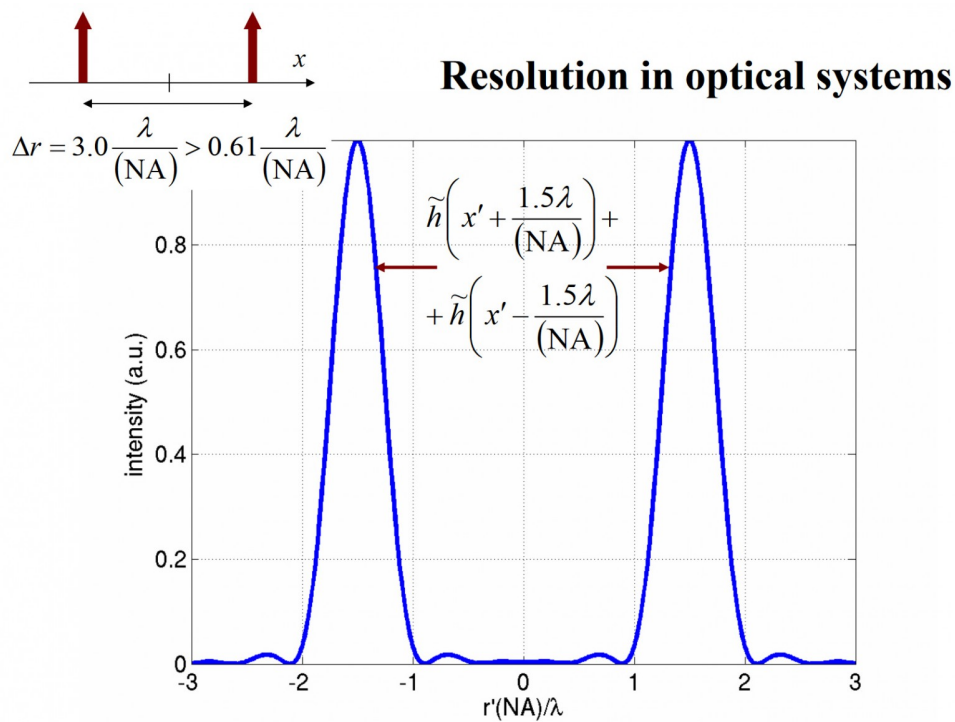


**The incoherent case:**  $\tilde{h}(x', y') = |h(x', y')|^2$



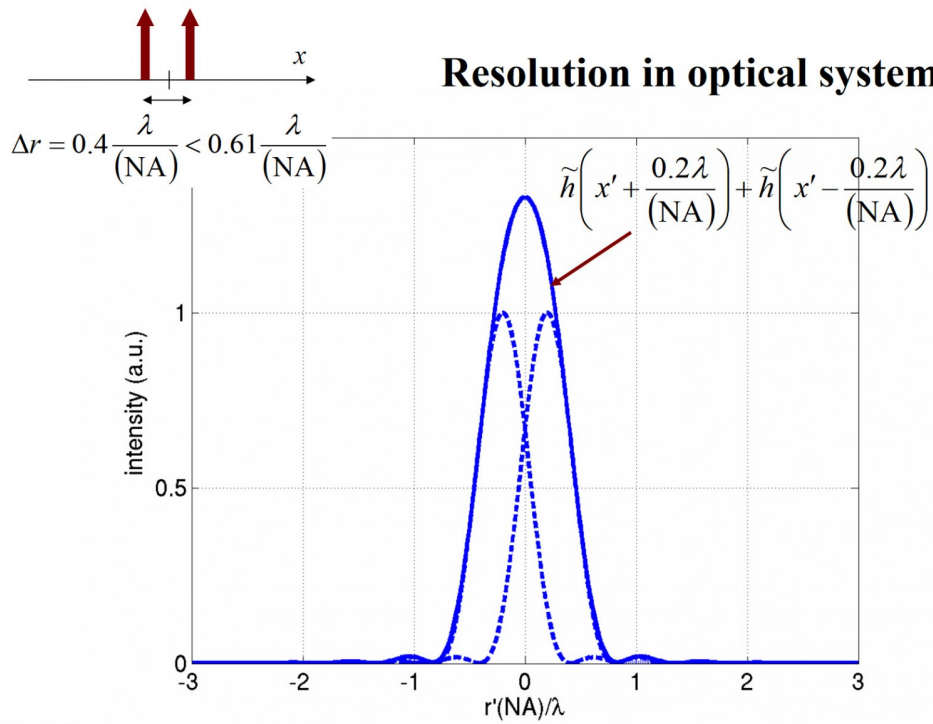
Now we go back to Resolution. How close together we can position two points and still distinguish them



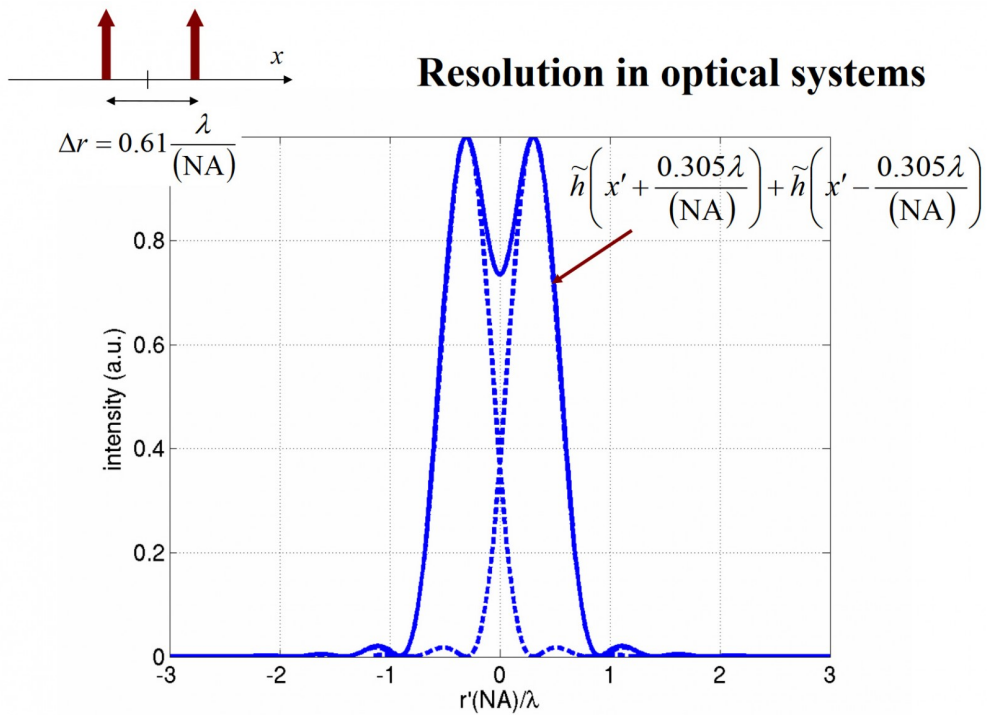


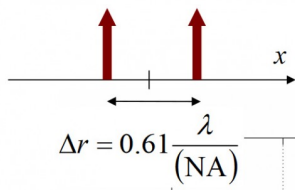


## Resolution in optical systems

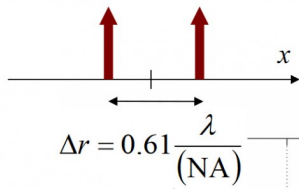
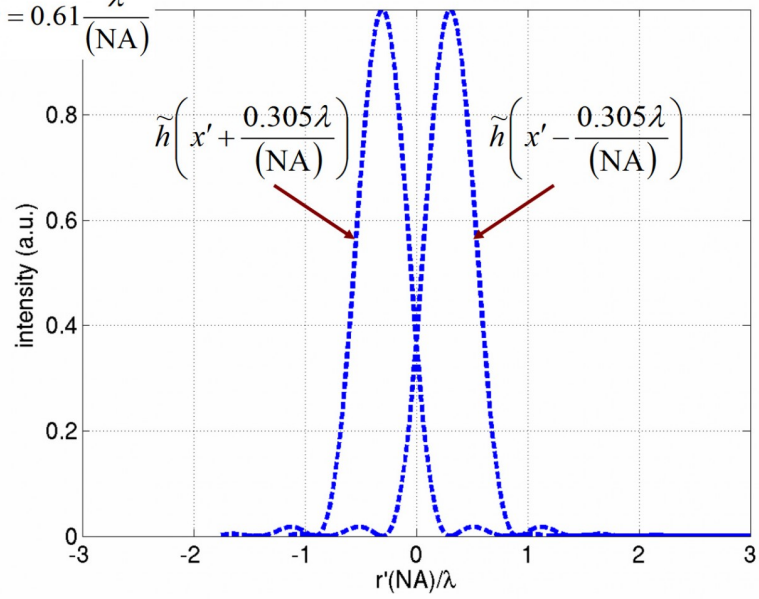


## Resolution in optical systems

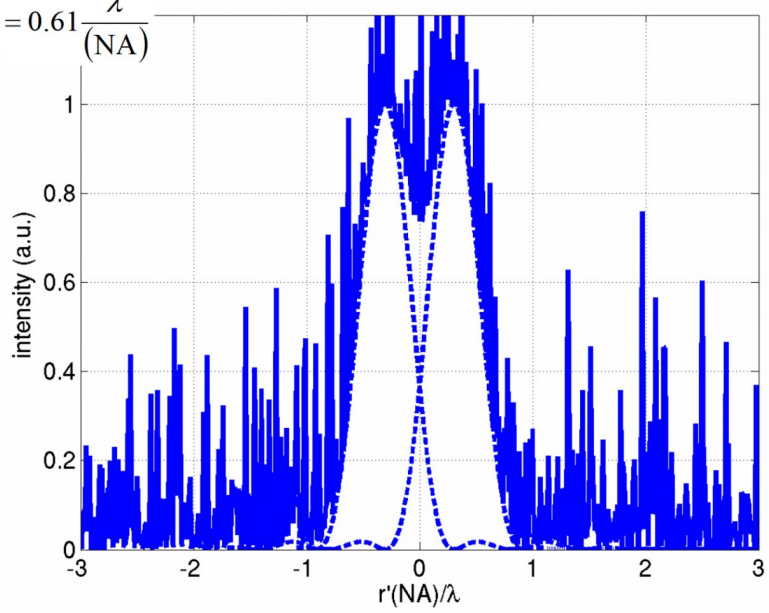


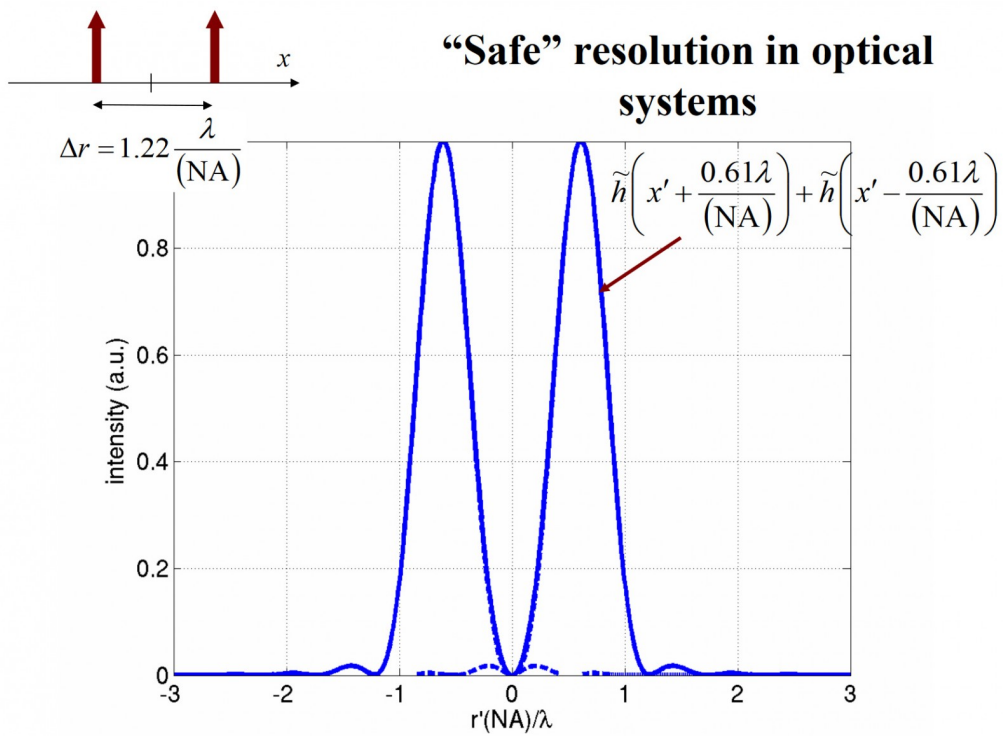


## Resolution in optical systems



## Resolution in noisy optical systems





Theoretical maximal resolution  $d_0$

$$d_0 = \frac{\lambda}{n \cdot A_{\text{Objective}} + n \cdot A_{\text{Condenser}}}$$

Simplified formula (wo condensor) for resolution  $d_0$

$$d_0 = \frac{\lambda}{2 n \cdot A_{\text{Objective}}}$$

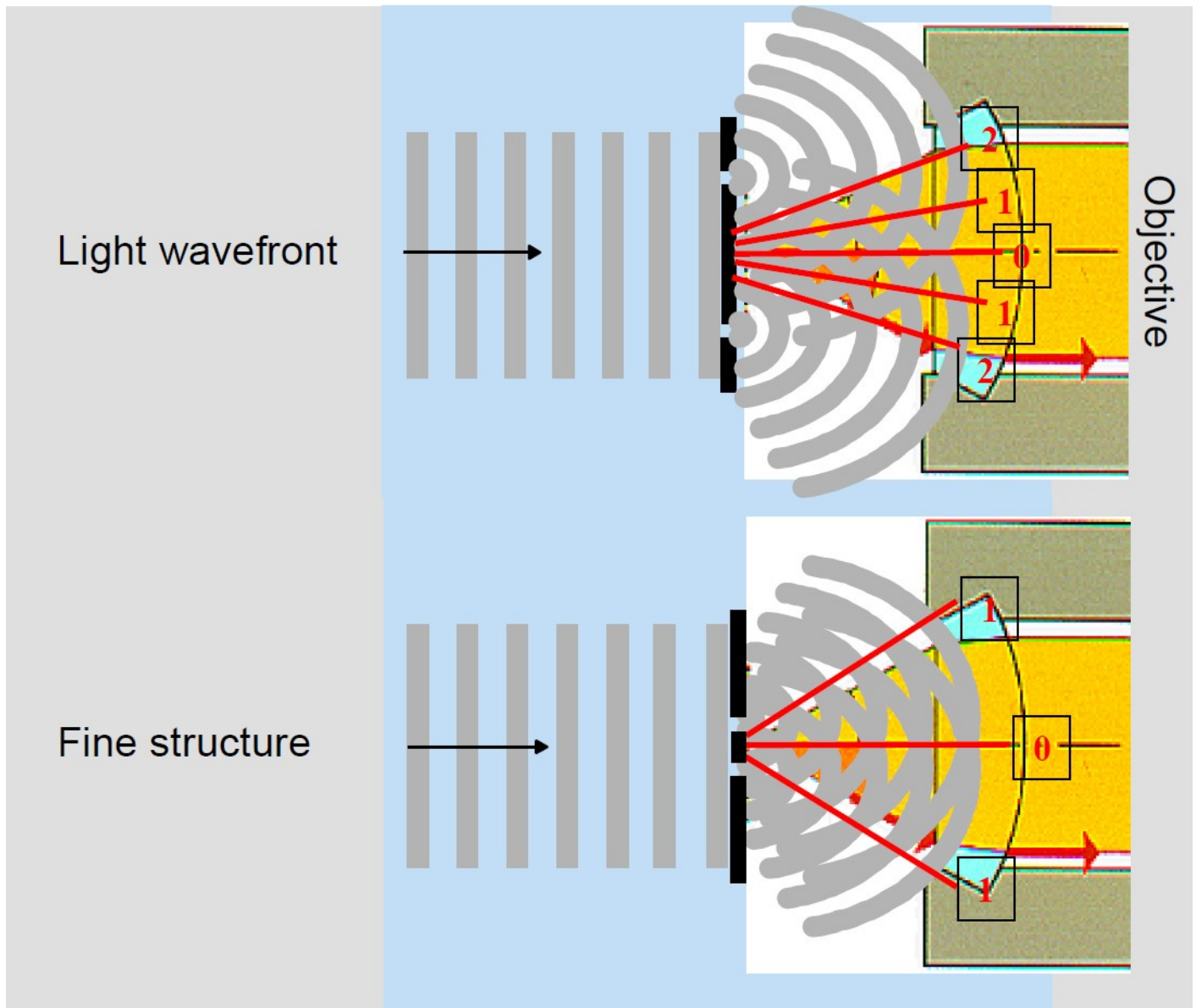
Maximal resolution  $d_0$  in reality

$$d_0 = \frac{1.22 \times \lambda}{2 n \cdot A_{\text{Objective}}}$$

Example

Green light  $\lambda = 550 \text{ nm}$ ,  $n \cdot A = 1.4$  (Oil immersion)  
 $d_0 = 671 \text{ nm} / (2 \times 1.4) = 239 \text{ nm} = 0.239 \mu\text{m}$

More intuitive approach



Notes from:

<http://web.mit.edu/2.710/Fall06/2.710-wk12-b-sl.pdf>

<https://links.uwaterloo.ca/amath353docs/set11.pdf>

<https://www.thefouriertransform.com/pairs/box.php>

<http://www.phys.unm.edu/msbahae/Optics%20Lab/Fourier%20Optics.pdf>

# Super Resolution Techniques

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Revision #13

Created 25 August 2021 16:11:10 by Glenn Fried

Updated 17 January 2024 17:16:29 by Glenn Fried