Resolution and Diffraction

Why are optical systems limited in resolution?

Optics Club MDC 03 May 2017

Outline

Theoretical Background

- Diffraction
- Point Spread Function
- Optical Resolution
- Fourier Optics

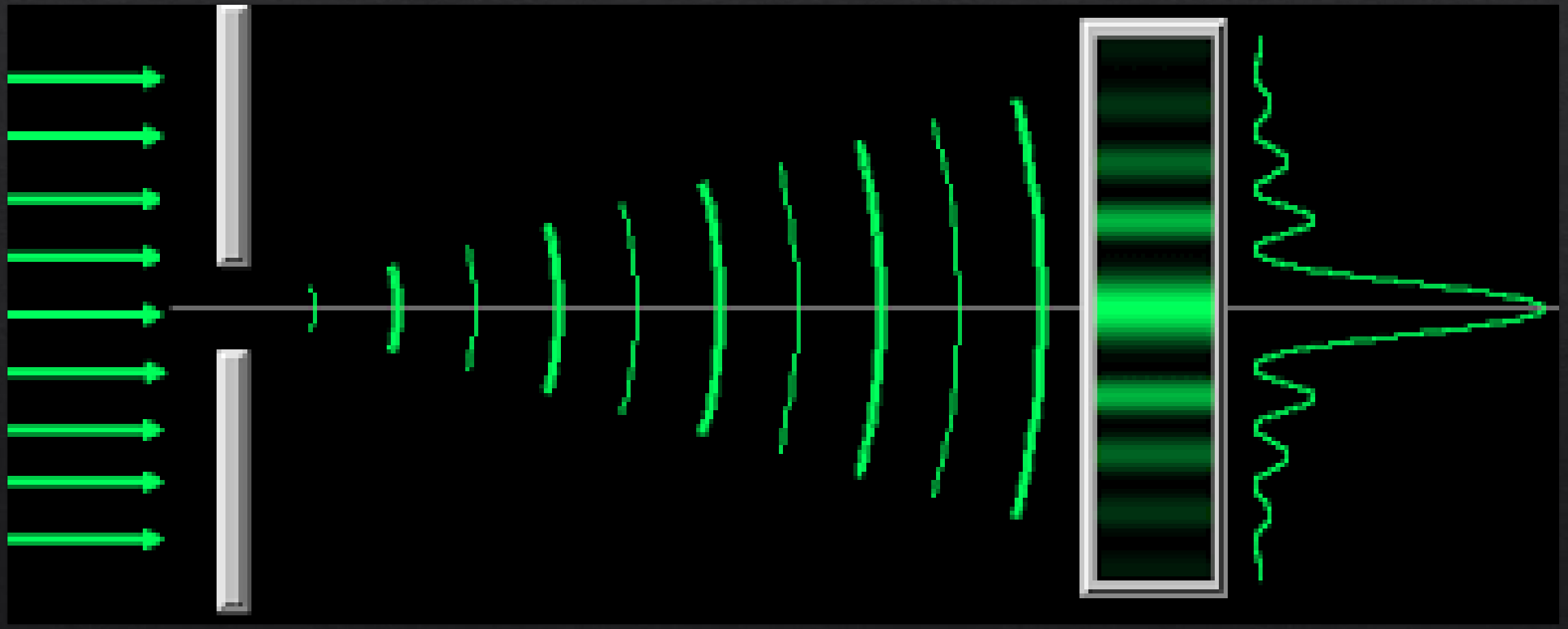
Abbe's Theory of Image Formation

Experiment

Part I: Theoretical Background

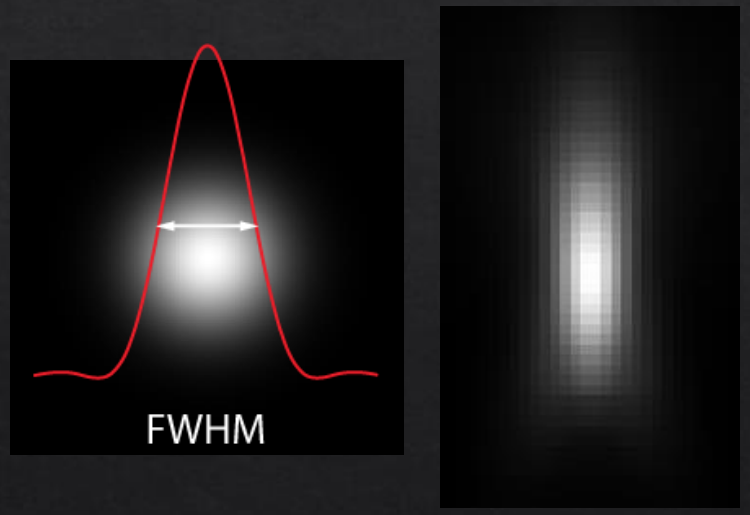
Diffraction, Point Spread Function, Image Formation, Optical Resolution, Fourier Optics, Spatial Frequencies

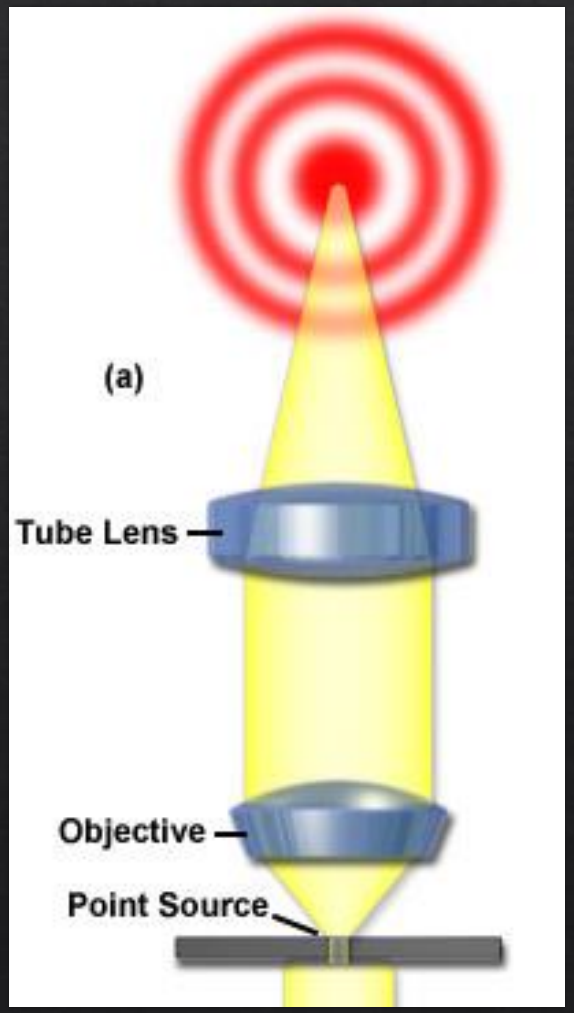
Diffraction



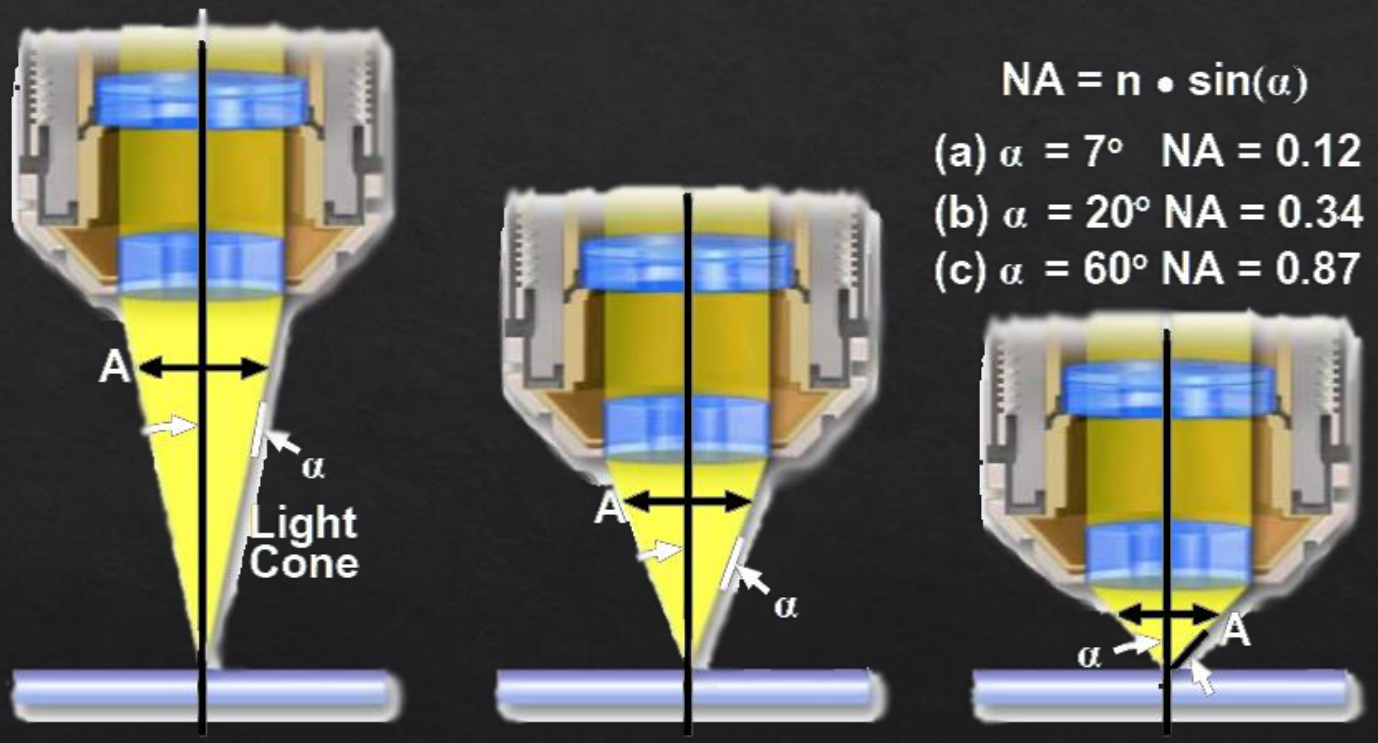
Point Spread Function (PSF)

- image of a **point object** → **point spread function**





Numerical Aperture



$NA = n \bullet \sin(\alpha)$

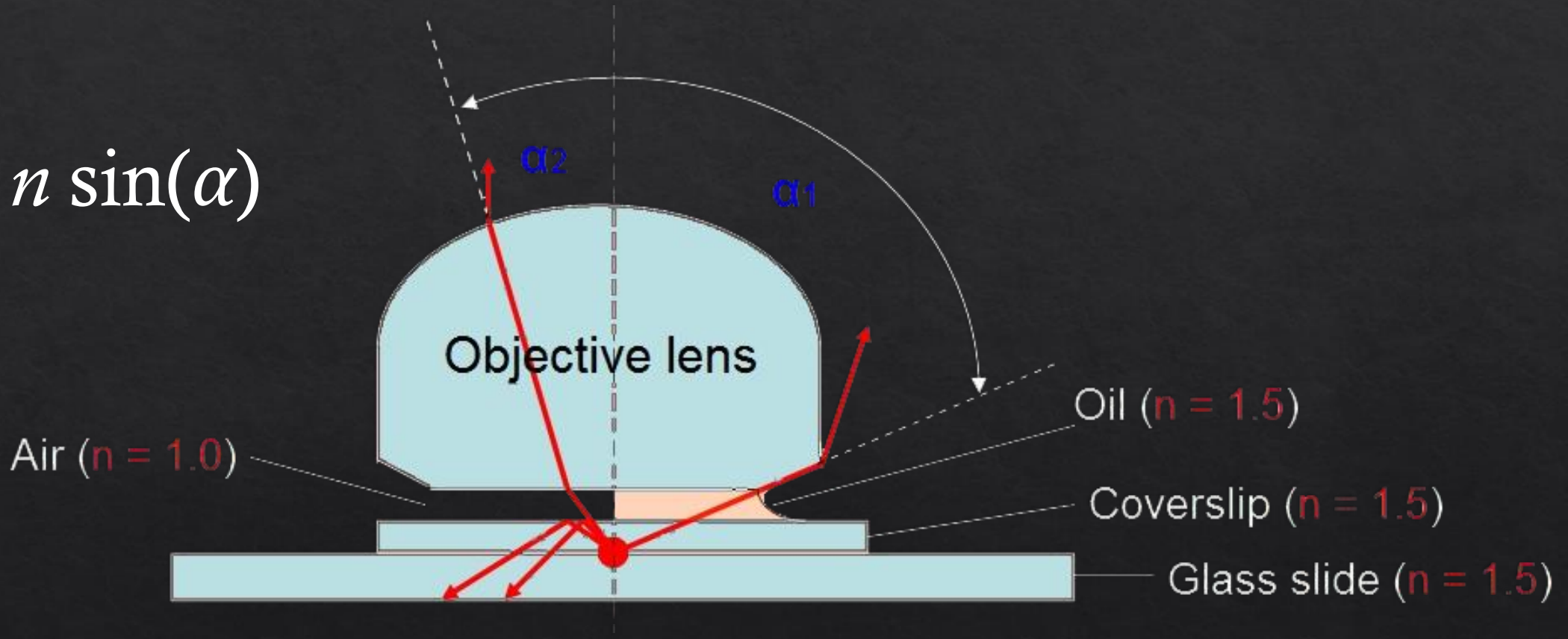
(a) $\alpha = 7°$ NA = 0.12

(b) $\alpha = 20°$ NA = 0.34

(c) $\alpha = 60°$ NA = 0.87

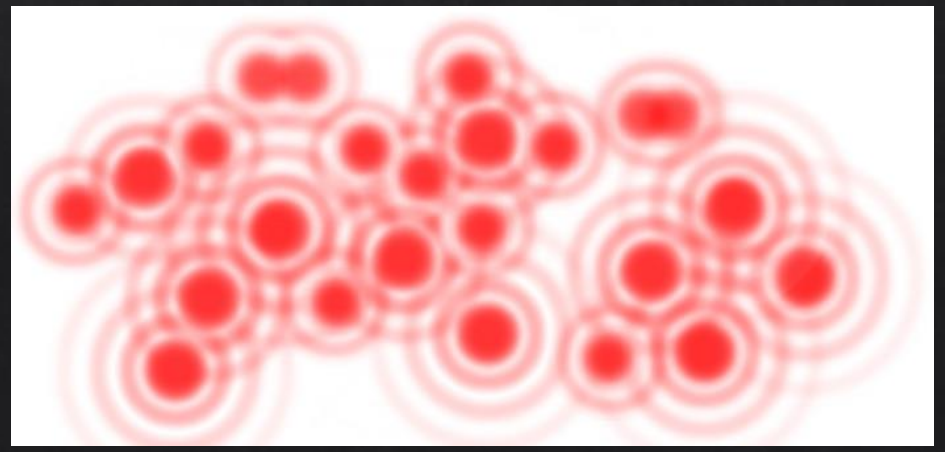
Numerical Aperture

$$NA = n \sin(\alpha)$$



Generalization: Every object consists of points!

The **image** formed by an optical system can be considered the **convolution** of the **sample** with the **point spread function**



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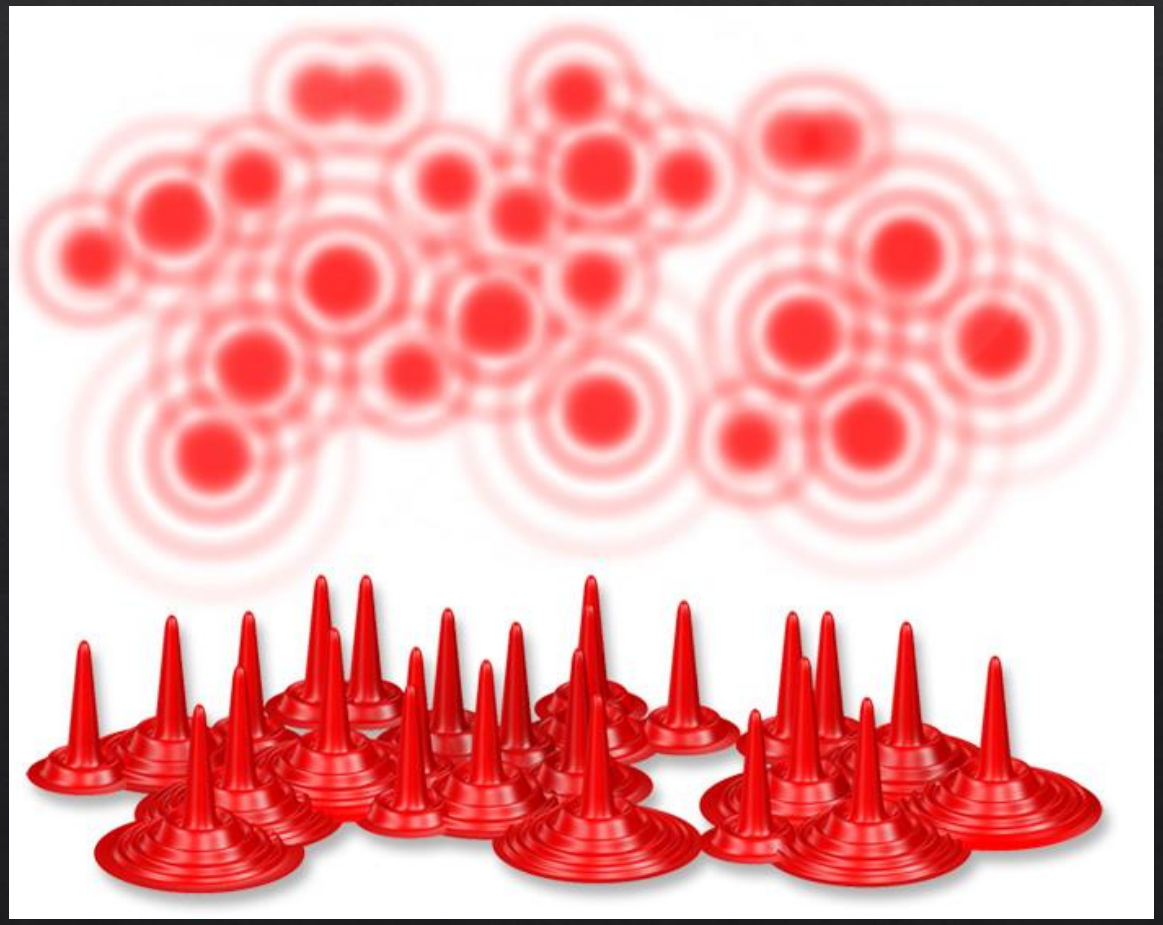
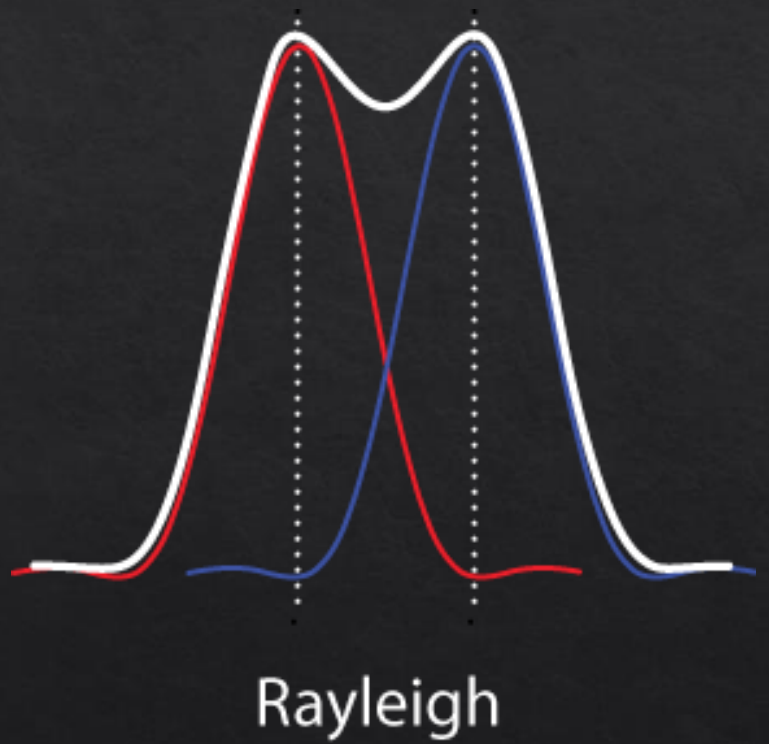
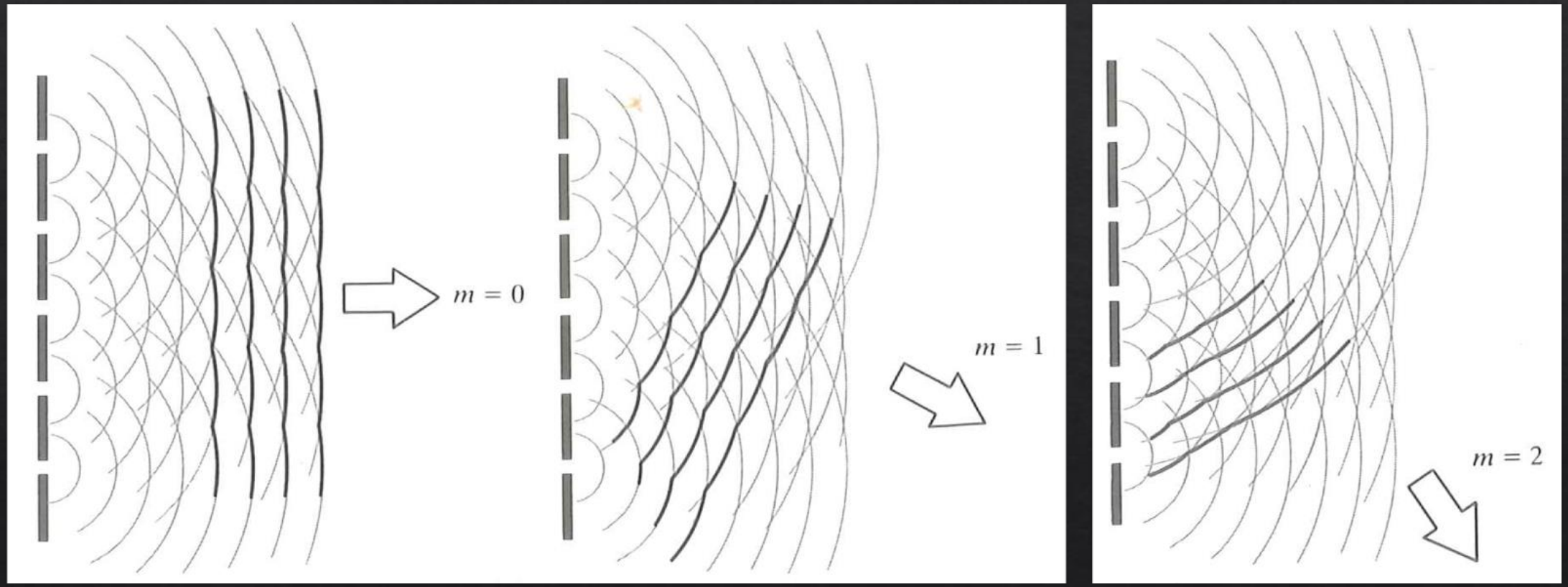


Optical Resolution

The **distance** at which two objects can still be distinguished is the optical **resolution**



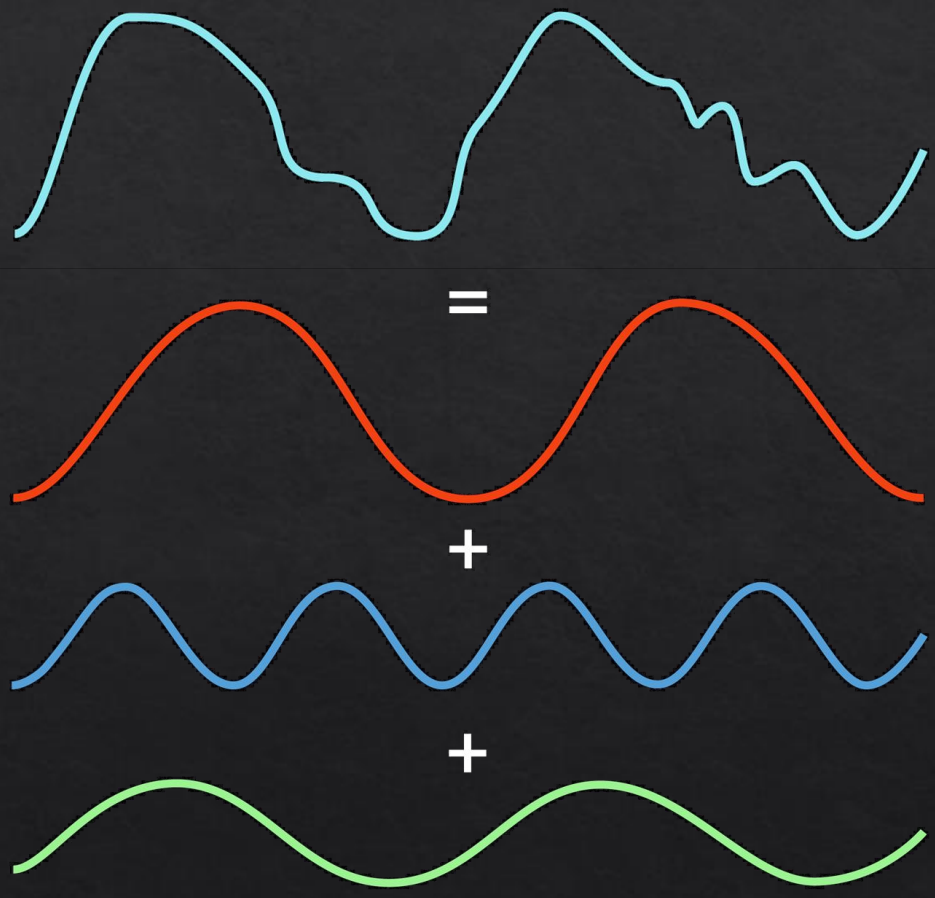
Diffraction by a grating

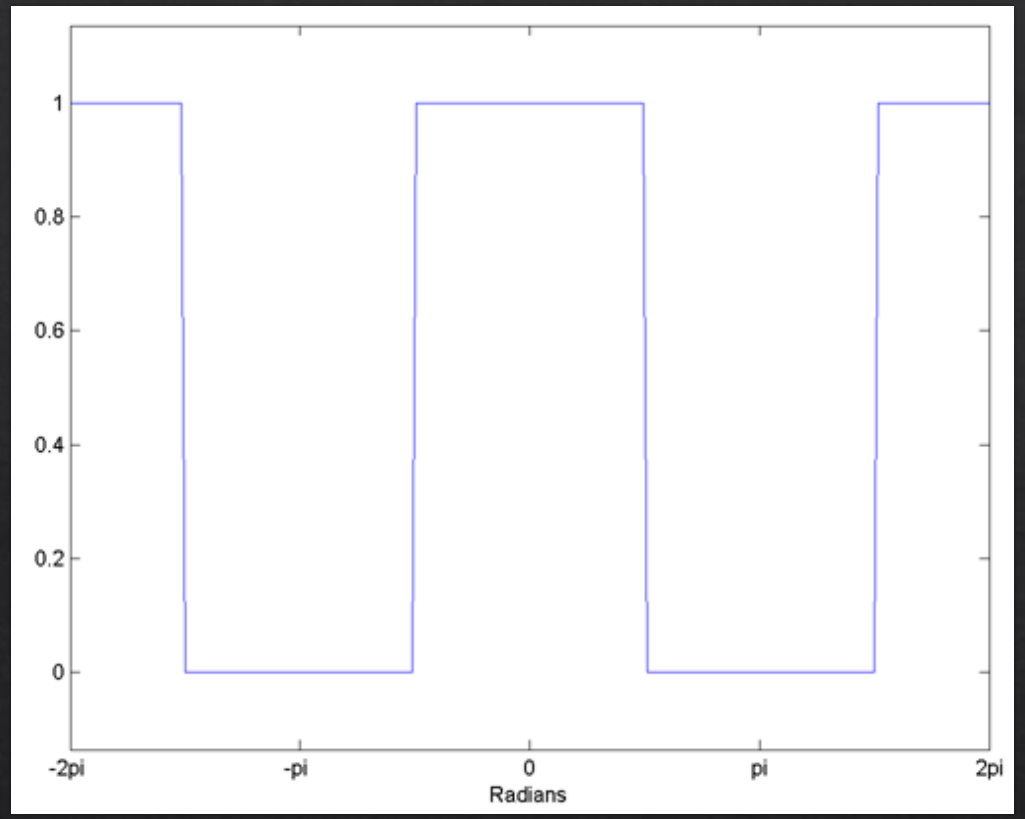


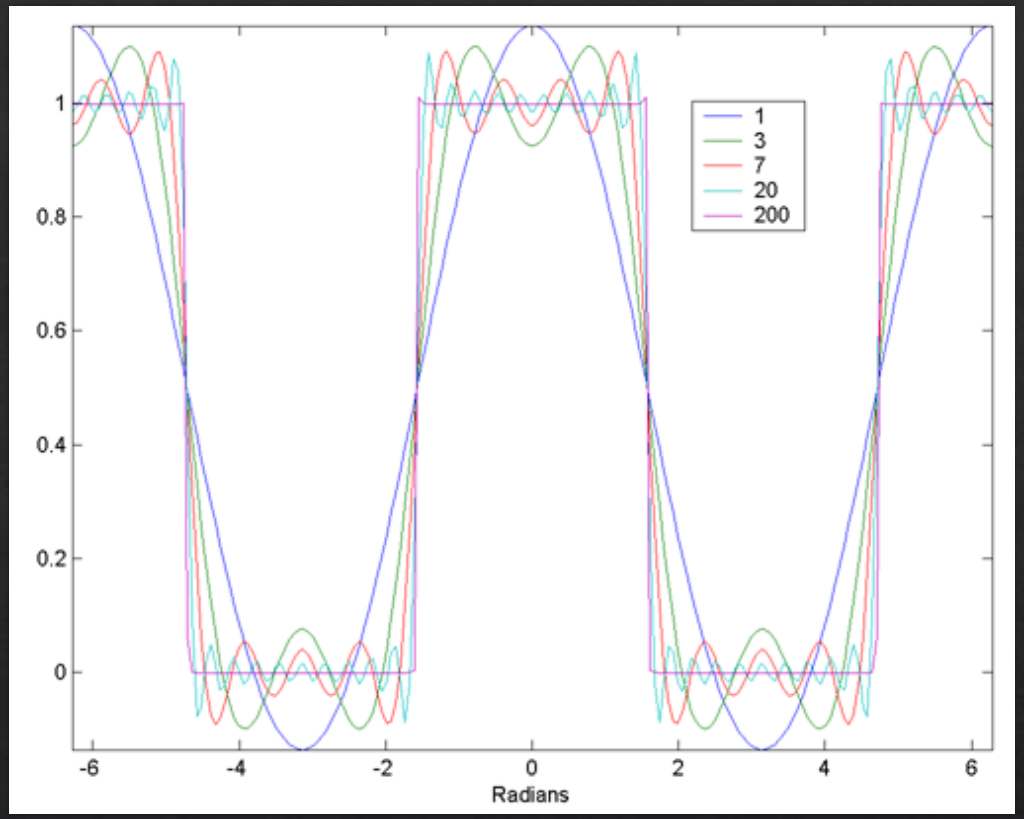
Generalization: Everything is periodic!

Fourier Analysis:

general functions may be represented or approximated by **sums of** simpler **trigonometric functions**





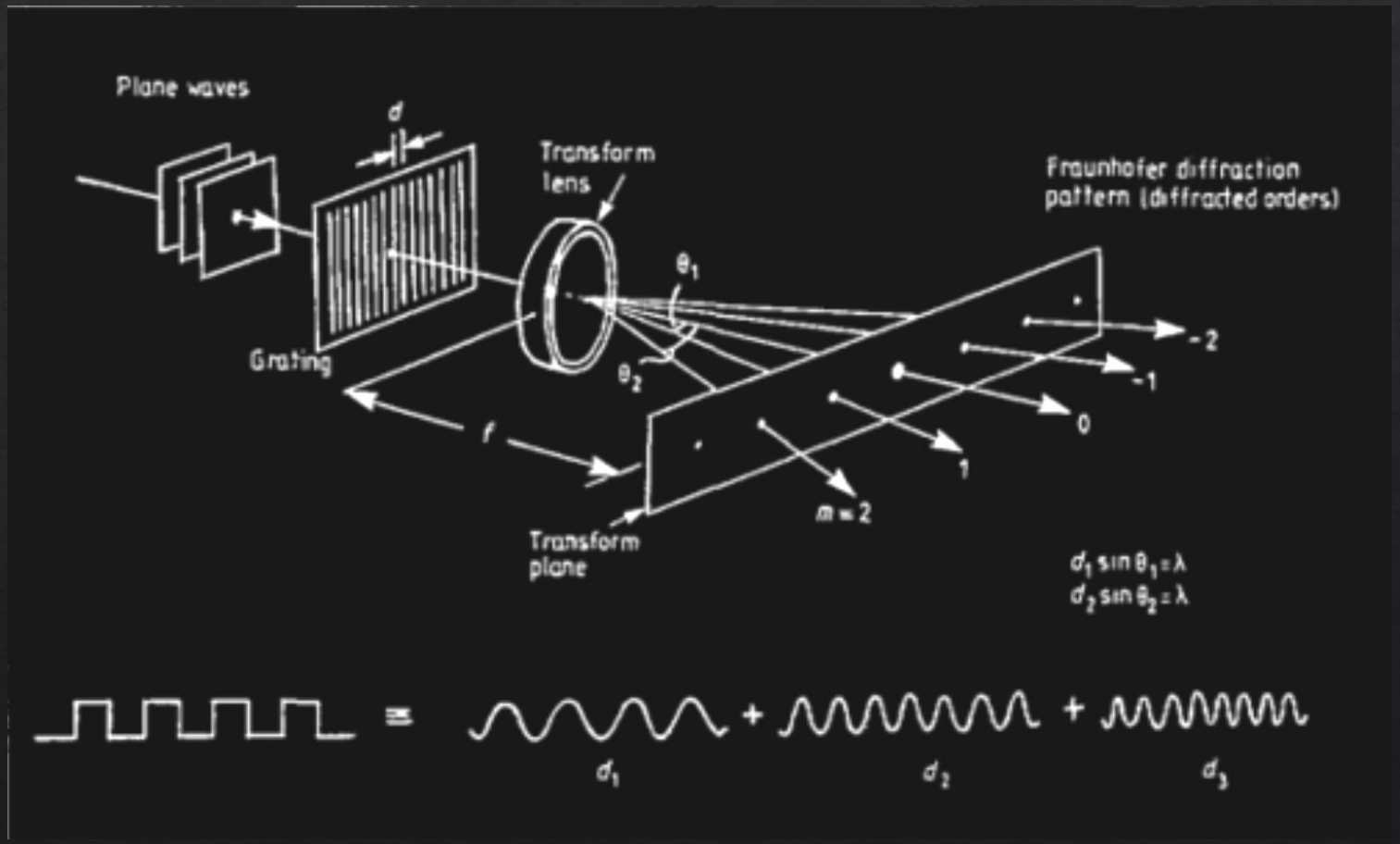


Approximation becomes better the more functions (of increasing frequency) are added

Fourier Optics

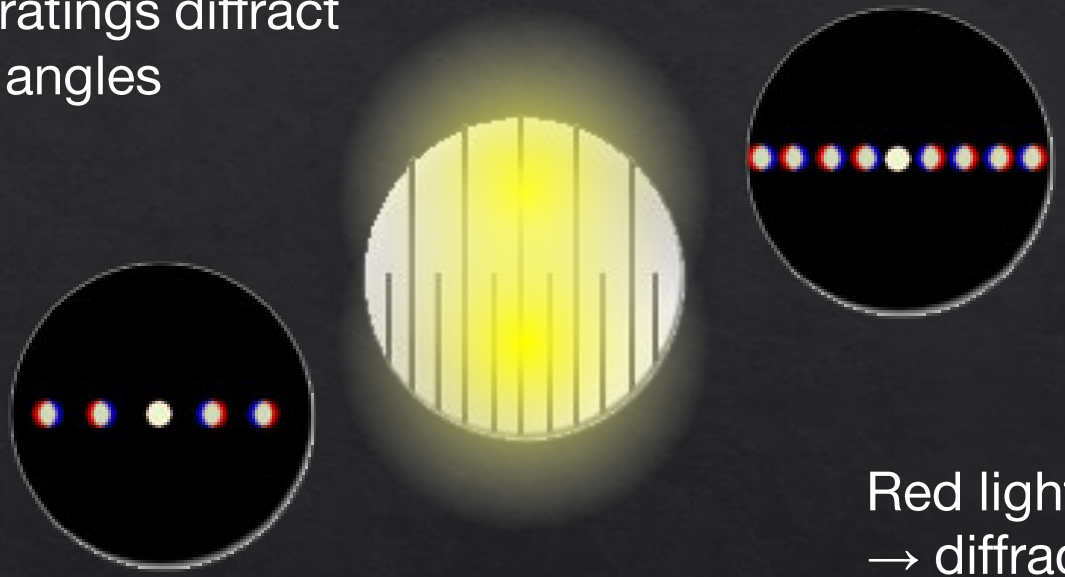
Fourier Transform: integral transform that re-expresses a function in terms of sine waves

A lens performs a **two-dimensional Fourier Transform** of the image in its focal plane

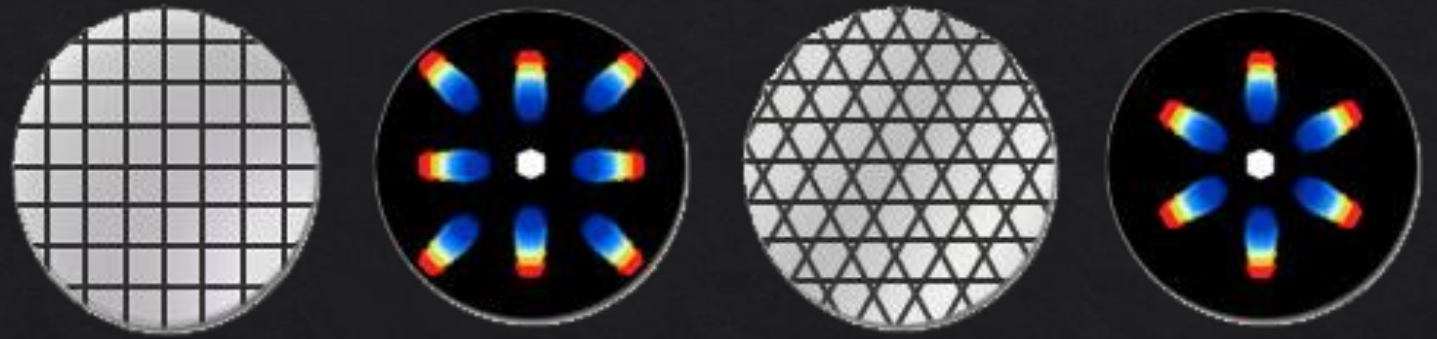


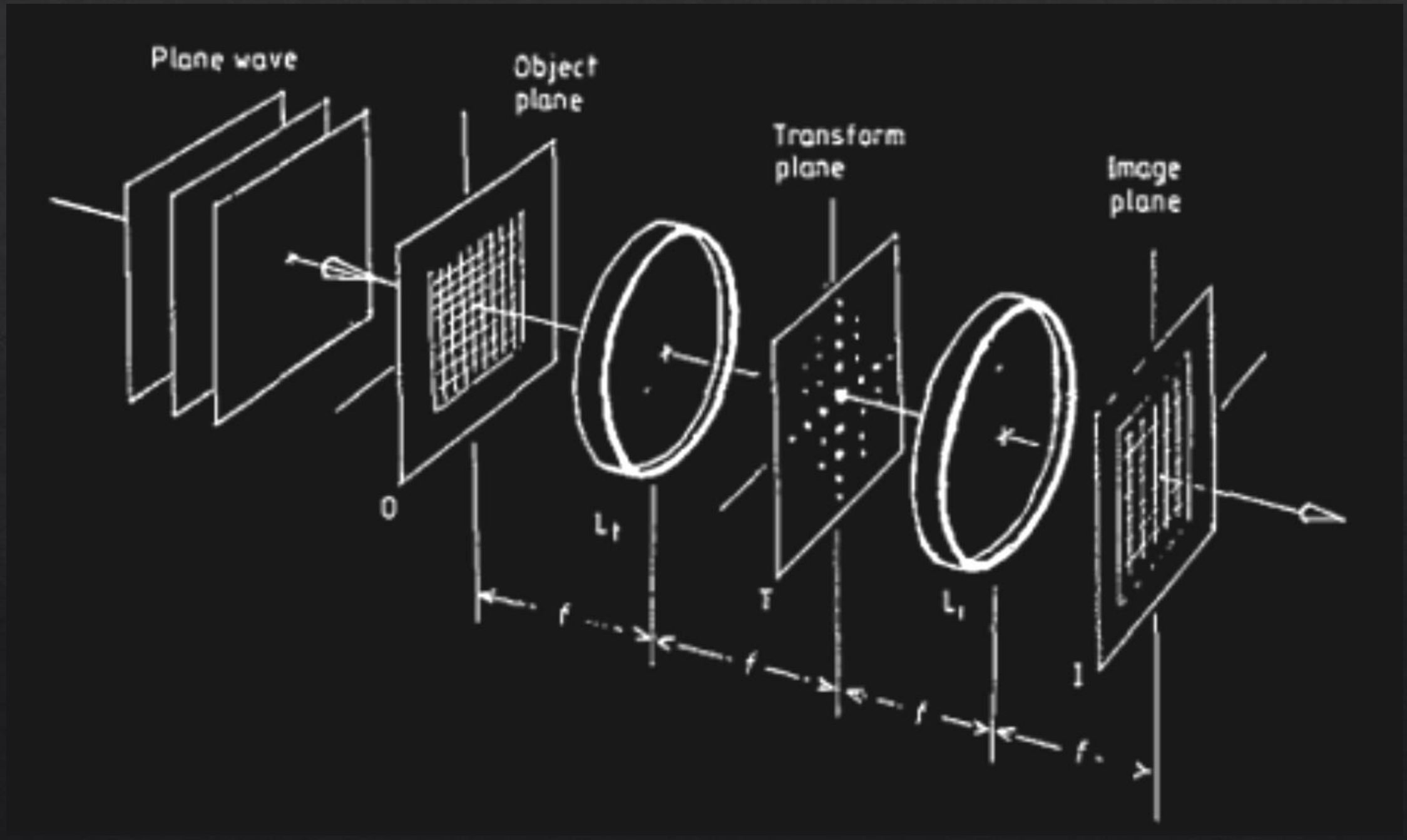
White light diffraction

Inverse scaling
→ finer gratings diffract to higher angles



Red light is diffracted stronger than blue light
→ diffraction angle scales with **wavelength**




Plane wave
Object plane
Transform plane
Image plane
O
L1
T
L1
I
f
f
f
f

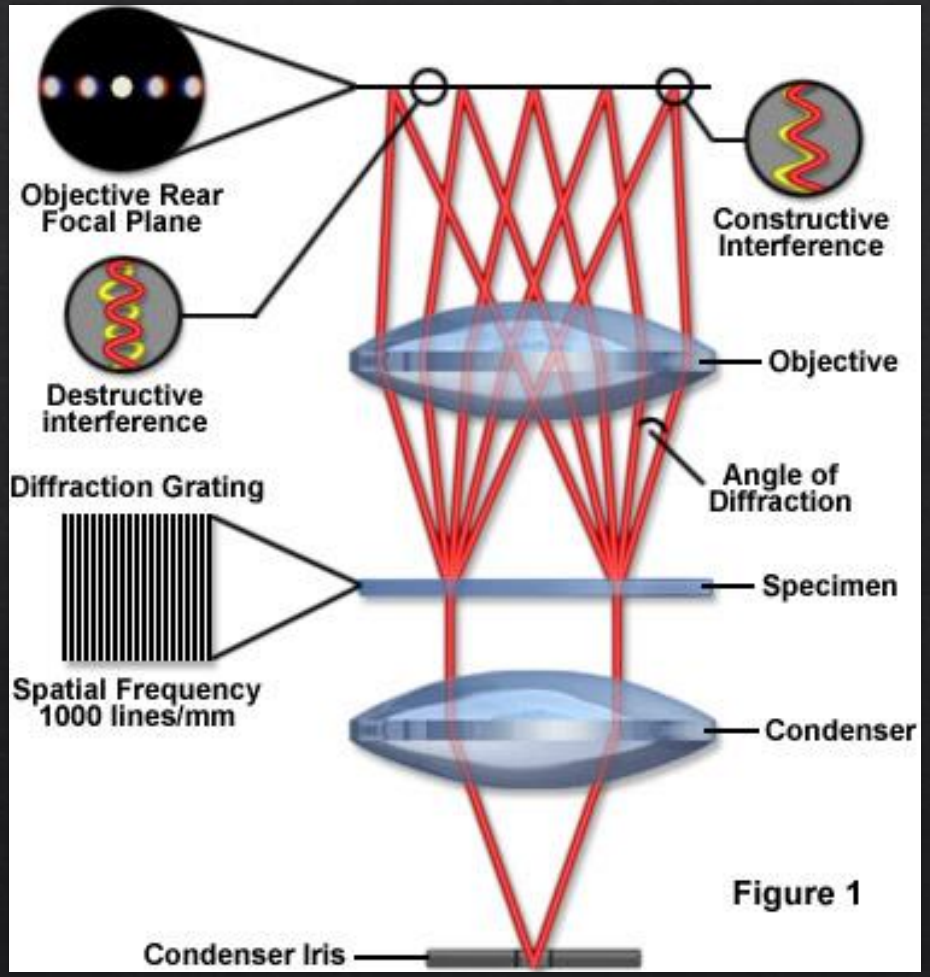
Summary

- Samples can be approximated by periodic functions
- Gratings of finer period diffract light stronger (to higher angles)
- Higher (diffraction) angles focus further outside in the **back focal plane** of a lens
  - Also called higher **spatial frequencies**
- The back focal plane corresponds to the 2D **Fourier Transform** of the sample

Part II

Abbe‘s theory of image formation

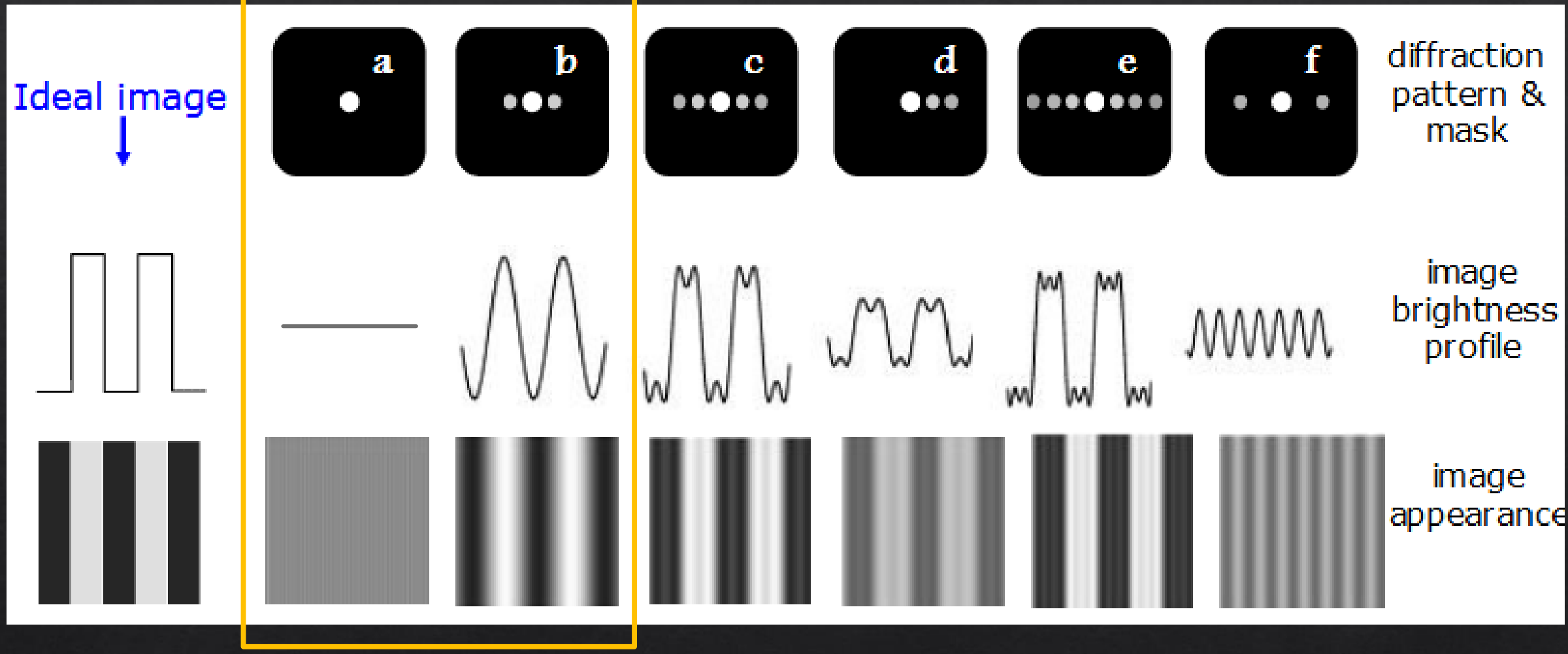
Abbe‘s theory of image formation



Abbe's theory of image formation

- details of a specimen will be **resolved if the objective captures 2 orders of light**
  - such as the 0th & 1st order of diffraction
  - the more diffracted orders are captured by objective, the more accurate the image
- with an **immersion medium** of higher refractive index than air, the angle of the diffracted orders is reduced
  - oil immersion objectives can capture more diffracted orders and yield better resolution than dry objective
- blue light is diffracted at a lower angle than red light
  - a lens of a given aperture may capture more orders with blue light

$$d = \frac{\lambda}{2n\sin\alpha}$$



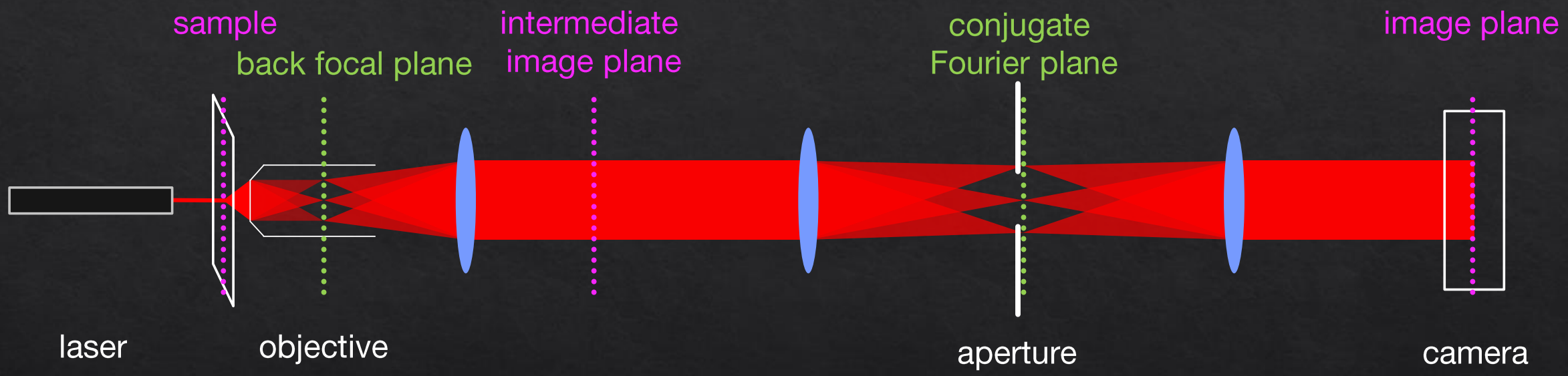
Fourier filters can be a versatile optical tool

Today‘s experiment

Part III: Experiment

Diffraction orders in the back focal plane of an objective

Part II: Experiment



Quiz

The line spacing on a CD is approximately 1.6 um. Which **numerical aperture** do we need to chose to resolve it under a parallel 670 nm laser illumination?

$$NA > \lambda/d = 670/1600 = 0.42$$

Fourier aperture

Open

Closed