Microscopy

CS/CME/BioE/Biophys/BMI 279

Oct. 21, 2021

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Outline

- Microscopy: the basics
- Fluorescence microscopy
- Resolution limits
  - The diffraction limit
  - Beating the diffraction limit

Microscopy: the basics

Most of what we know about the structure of cells come from imaging

- Light microscopy, including fluorescence microscopy

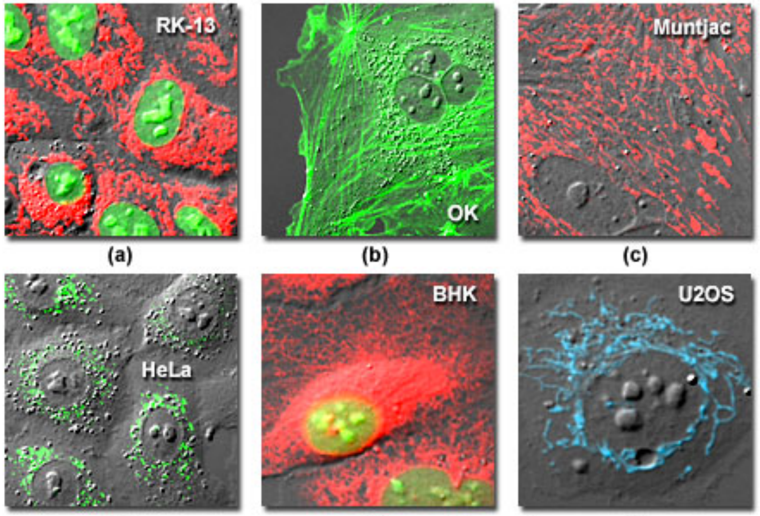


Figure 1

https://www.microscopyu.com/articles/livecellimaging/livecellmaintenance.html

- Electron microscopy

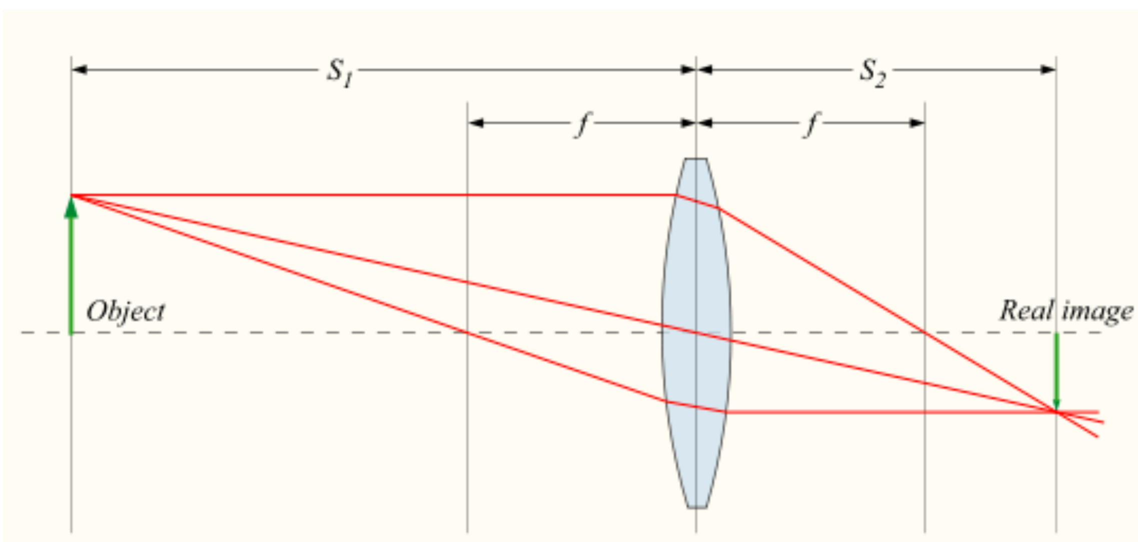
http://blog.library.gsu.edu/wp-content/uploads/2010/11/mtdna.jpg

Light microscopy

- Basic idea:
  - Shine light on a biological sample (i.e., one or more cells)
  - Measure the light that is *reflected* or *transmitted*
  - Use lenses
    - Why do we need lenses in a microscope?

Lenses in microscopy

- The lenses in a microscope do two things:
  - Magnify the image
  - *Focus* the image, so that much of the light coming from a particular point in the sample ends up focusing on a particular point on either your retina or a sensor (e.g., CCD)
    - You need a lens to form a clear image, even if you have a very high-resolution sensor



https://upload.wikimedia.org/wikipedia/commons/thumb/7/71/Lens3.svg/542px-Lens3.svg.png

Fluorescence microscopy

Fluorescence microscopy: basic idea

- Suppose we want to know where a particular type of protein is located in the cell, or how these proteins move around
- We can’t do this by simply looking through a microscope, because:
  - We (usually) don’t have sufficient resolution
  - The protein of interest doesn’t look different from the ones around it
- If only the protein would glow!
- Can we get a protein (or other molecule of interest) to glow?

Fluorescence microscopy: basic idea

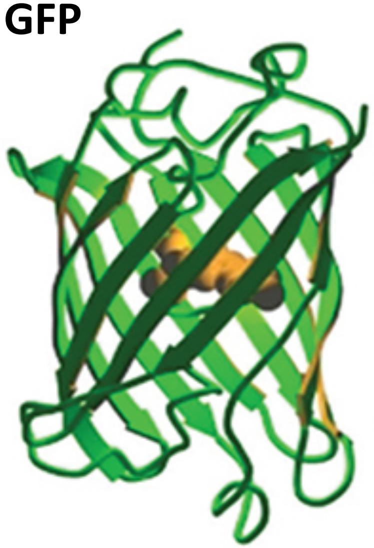
- Make the molecules of interest glow
- Attach a fluorophore (fluorescent molecule) to the molecule of interest
- When you shine light of a particular wavelength on a fluorophore, it emits light of a different wavelength
  - Additional advantage: not only does the molecule glow, the light it emits has a different wavelength than the incident illumination, making it easier to isolate

Fluorophores

- Fluorophores can themselves be either proteins or much smaller molecules
  - Among the most widely used is green fluorescent protein (GFP)

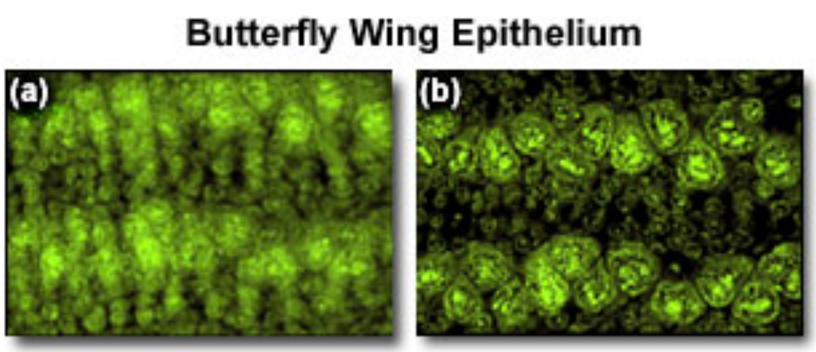
The Nobel Prize in Chemistry 2008 was awarded jointly to Osamu Shimomura, Martin Chalfie and Roger Y. Tsien *"for the discovery and development of the green fluorescent protein, GFP"*.

GFP



Fluorescence microscopy images

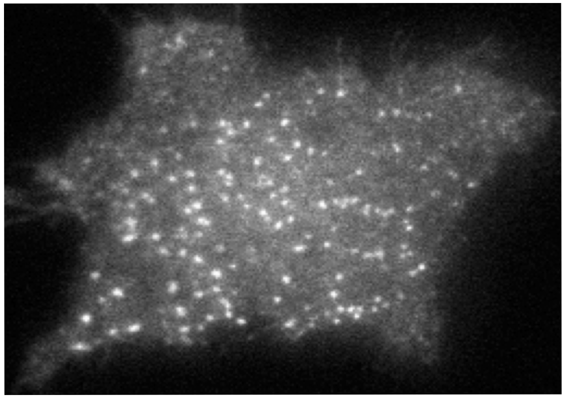
- There are many types of fluorescence microscopy: wide-field, confocal, TIRF (total internal reflectance fluorescence), etc.
  - You're not responsible for knowing them



Wide-field Confocal

http://www.microscopyu.com/articles/confocal/confocalintrobasics.html

TIRF

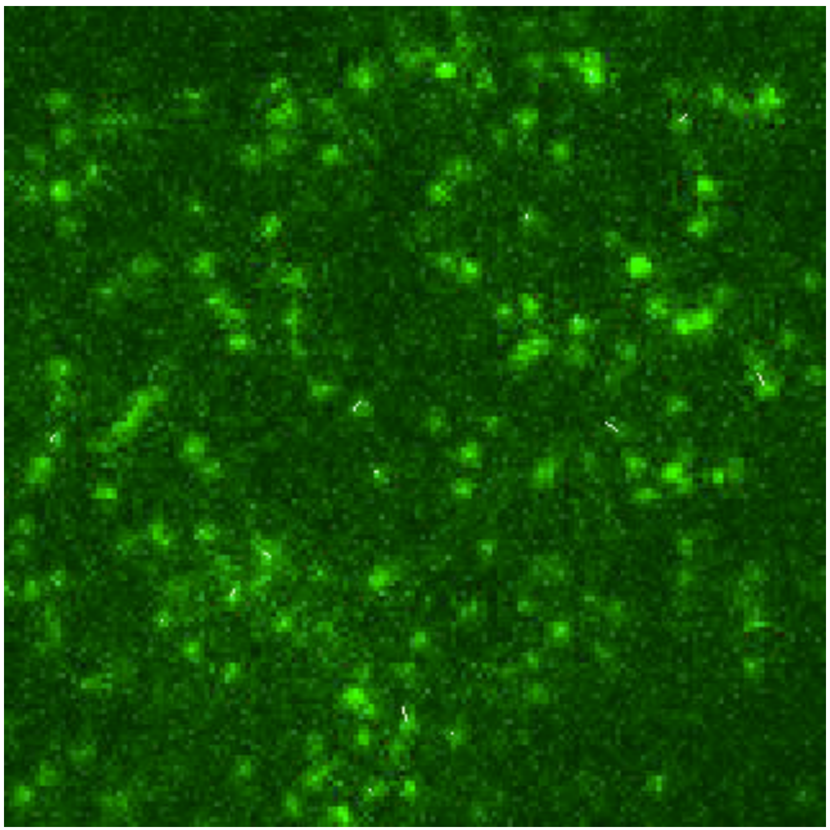


Von Zastrow lab, UCSF

Analyzing this data quantitatively involves the types of image analysis we discussed in previous lectures, and more

Single-molecule tracking

- If the density of fluorescent molecules is sufficiently low, we can track individual molecules
  - Doing this well is a challenging computational problem



Data: Bettina van Lengerich, Natalia Jura
Tracking and movie: Robin Jia

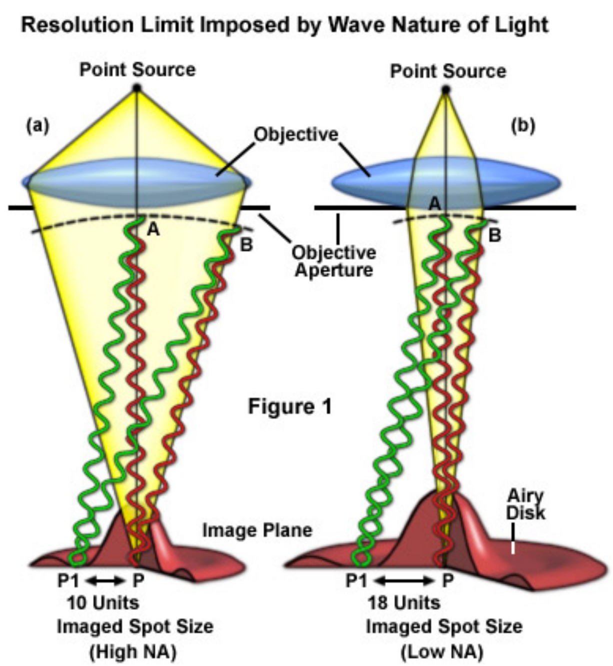
Resolution limits

Resolution limits

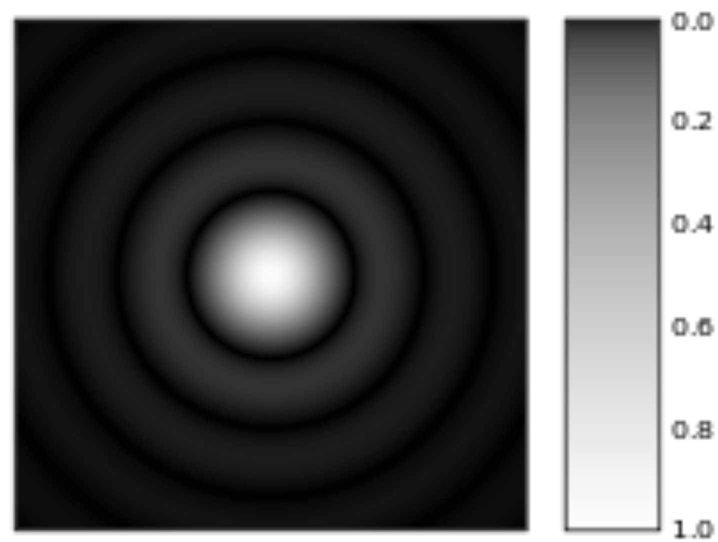
The diffraction limit

A limit on focusing light

- The physics of light—in particular, the fact that it is a wave—impose a fundamental limit on how well a lens can focus it
- The light from a single point in space will not focus to a single point
- Instead, it will focus to a disk-like pattern called an “Airy pattern”
  - This means the observed image will be slightly blurred
  - In fact, we can think of the observed image as the true image convolved with the Airy pattern. This constitutes a low-pass filter.

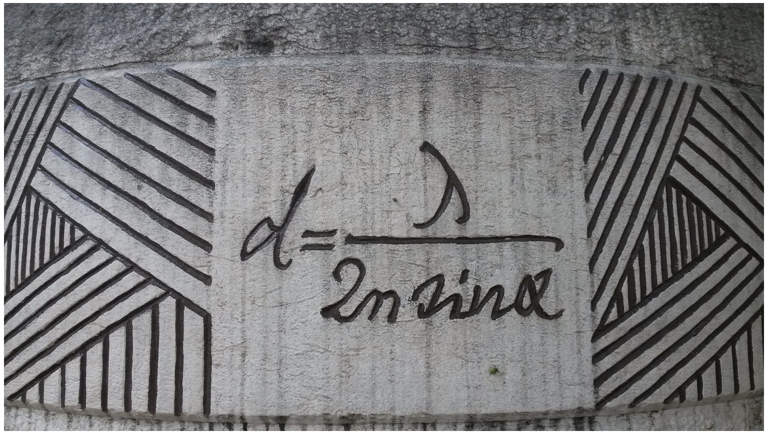


Airy pattern



You’re not responsible for details of the underlying physics here

The diffraction limit



http://en.wikipedia.org/wiki/STED_microscopy#mediaviewer/File:Ernst-Abbe-Denkmal_Jena_F%C3%BCrstengraben_-_20140802_125708.jpg

- This limit on how well one can focus light is known as "the diffraction limit"
  - It's literally "written in stone" in Jena, Germany (on a memorial to Ernst Abbe, who published it in 1873)
- The radius *d* of the Airy disk (the central spot of the Airy pattern) is proportional to the wavelength λ of the light
- It also depends on some other parameters that determine the "numerical aperture" ($n \sin\theta$)
  - You don't need to worry about this
  - It's usually between 0.1 and 1

The bottom line

- Resolution limit of a light microscope:
  - The wavelength of visible light is 400–700 nm
  - A light microscope can't distinguish points that are closer than 200 nm
- Many cellular structures are smaller than this. A protein is just a few nm across.

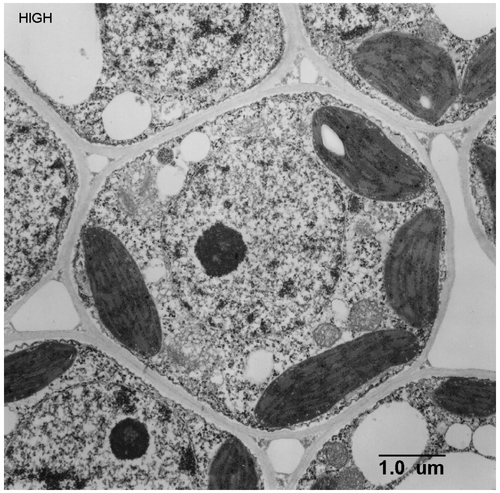
Resolution limits

Beating the diffraction limit

Option 1: Decrease the wavelength

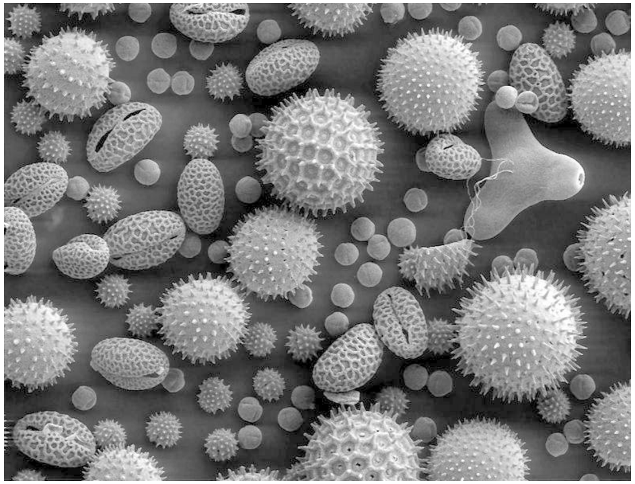
- Higher-frequency radiation (e.g., x-rays) has shorter wavelengths and thus allows higher resolution
  - It also damages the sample more
- It's possible to image with electrons, which have a *much* shorter wavelength (~.1 nm)
  - Electron microscopy can thus achieve much higher resolution
  - Disadvantages: can't use living cells, and molecules of interest won't glow

Transmission electron microscopy



http://www.cas.miamioh.edu/~meicenrd/ANATOMY/Ch2_Ultrastructure/Tempcell.htm

Scanning electron microsopy



http://www.newscientist.com/data/images/ns/cms/dn14136/dn14136-1_788.jpg

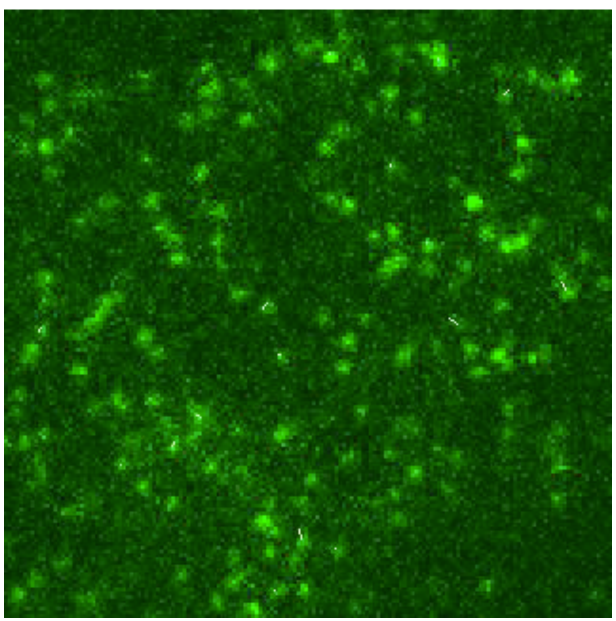
Option 2: super-resolution fluorescence microscopy

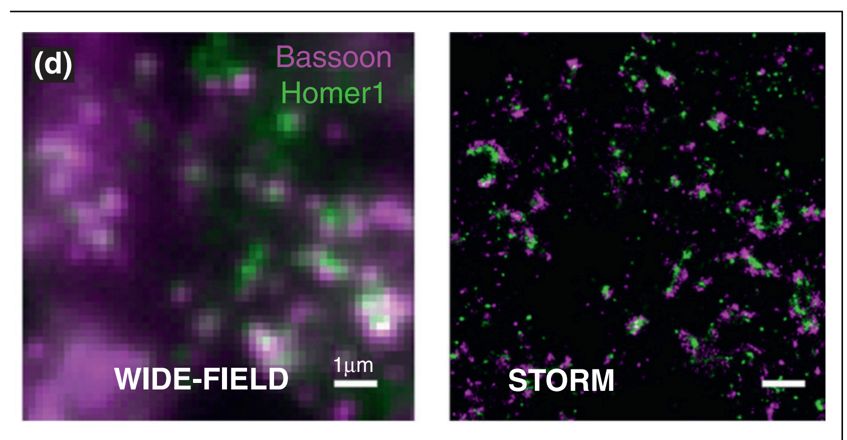
- A number of recently developed techniques achieve resolution well beyond the diffraction limit
  - This requires violating some of the assumptions of that limit
- I'll briefly describe the most popular of these techniques, known alternately as STORM (stochastic optical reconstruction microscopy) or PALM (photoactivation localization microscopy)

The Nobel Prize in Chemistry 2014 was awarded jointly to Eric Betzig, Stefan W. Hell and William E. Moerner *"for the development of super-resolved fluorescence microscopy"*.

STORM/PALM

- If we have only a few fluorophores in an image, we can localize them very accurately
- Thus by getting only a few fluorophores to turn on at a time, identifying their locations in each image, and combining that information (computationally) across many images, we can build a composite image of very high resolution





Sigrist & Sabatini, Current Opinion in Neurobiology 22:1-8, 2011