# (Biomedical Optics)

## 1- Introduction to inverse problems

Inverse problems refer to a type of problem in mathematics and science where the goal is to determine the input or cause of a given output or result. In other words, instead of starting with an input and calculating an output, we start with an output and try to determine what input or cause could have produced it. Inverse problems can be found in many different fields, including physics, engineering, geology, medicine.

In medicine is **medical imaging**, where inverse problems are used to reconstruct images of the internal structure of the body from measurements obtained by various imaging ways. For example:

1. Computed Tomography (CT), inverse problems are used to reconstruct 3D images of the body from a series of x-ray measurements.
2. Magnetic Resonance Imaging (MRI), inverse problems are used to reconstruct high-resolution images of the body from measurements of the magnetic fields generated by the body's tissues.
3. Positron emission tomography (PET).
4. Electron Tomography (ET).

- Inverse problems are also used in other medical applications, such as electroencephalography (EEG) and magnetoencephalography (MEG), where they are used to reconstruct the electrical or magnetic activity of the brain from measurements of the electric or magnetic fields outside the skull.

## 2- Radon Transform

The Radon transform is a mathematical operation that takes a function (usually an image) and transforms it into a set of line integrals. It is particularly important in the field of computed tomography (CT) imaging. The Radon transform is used to mathematically model how X-rays interact with tissues in the body, and by applying its inverse, a CT scanner can reconstruct a cross-sectional image of the internal structures of the body.

## 3- Inverse scattering and Imaging in transparent media

**Inverse scattering** is a mathematical technique used to reconstruct the properties of a medium, such as its shape, composition, or internal structure, based on the measurements of the scattered waves that are generated when an incident wave interacts with the medium. In other words, it is the process of determining the characteristics of an object or medium that cause the scattering of waves, rather than measuring the waves themselves. In medical imaging, inverse scattering can be used to create images of the internal structure of the body, such as the brain or the heart, by analyzing the scattering of x-rays, sound waves, or electromagnetic waves as they pass through the body.

**Imaging in transparent media:** refers to the process of using electromagnetic waves, typically visible light, infrared radiation, or x-rays, to obtain information about the internal structure of a transparent medium, such as biological tissue or glass. The waves interact with the material in different ways, depending on its composition and structure, and these interactions (include absorption, reflection, refraction, and scattering) are then measured and analyzed to produce an image of the material's internal structure. There are different types of imaging techniques that can be used to image transparent media, depending on the type of waves used and the specific properties of the medium being imaged.

- **Visible Light and Near-Infrared Imaging:**
  - Used in optical imaging techniques.
  - Biological tissues are often transparent to certain wavelengths of light in the visible and near-infrared range.
  - This transparency allows for non-invasive imaging of tissues, making these techniques valuable in medical diagnostics and research.
- **Infrared Radiation:**
  - Useful for imaging temperature variations in materials.
  - Can penetrate certain substances that visible light cannot.
- **X-ray Imaging:**
  - Utilizes high-energy X-rays.

- Valuable for imaging dense structures like bones and providing detailed views of internal structures, commonly used in medical diagnostics.

## 4-Applications to Computational Microscopy

Applications to Computational Microscopy refer to the use of computational methods and tools to improve the quality and efficiency of microscopy-based imaging techniques. Computational microscopy involves the use of mathematical algorithms, computer simulations, and machine learning techniques to enhance the resolution, contrast, and sensitivity of microscope images. where it's include a wide range of uses, including:

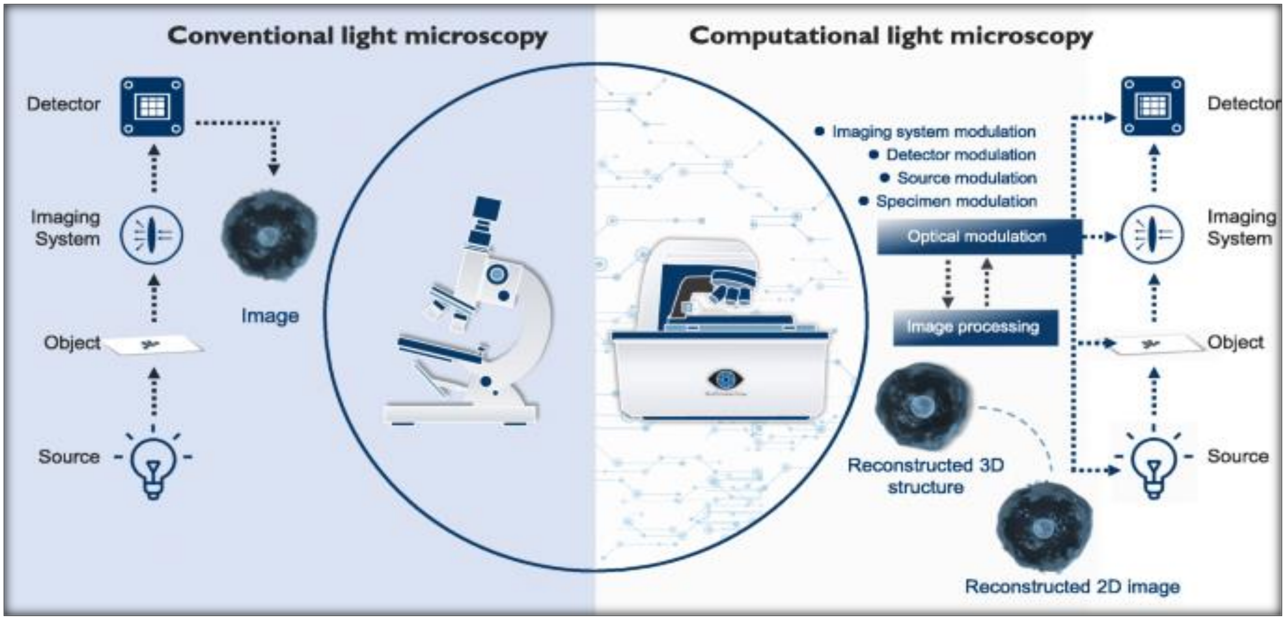
1-Imaging cells and analyzing microscopic images to understand the structure and function of cells.

2- Computational methods are employed to improve the accuracy and quality of microscopic images. Techniques such as deconvolution and super-resolution microscopy use mathematical algorithms to reconstruct high-resolution images from lower-resolution data, enhancing the overall image quality.

3-Using computer vision analysis to track the movement and interactions of particles and cells in real-time.

4-Using microscopic images to study geological patterns and identify materials in mineral samples and rocks.

❖ The ultimate goal of applications to computational microscopy is to extract more information from microscopy images, enabling researchers to better understand biological systems at the cellular and molecular level, and to develop new therapies for diseases.




❖ **Conventional Light Microscopy:**

➢ **Components of a Typical Light Microscope:**

1. **Light Source:** Provides illumination.
2. **Imaging System:** Consists of lenses and optical components to capture and transmit light.
3. **Light Detector:** Captures the transmitted light and converts it into an image.

- **Imaging Mechanism:**
- Light from the source interacts with the specimen, leading to processes like absorption, scattering, or fluorescence.
- The resulting light is collected by the optical system and focused onto an image sensor.
- The image sensor records the magnified digital image in a point-to-point manner.
- **Limitations:**
- Intensity-only detection.
- Single-view observation.
- Two-dimensional (2D) planar recording.
- Diffraction limits.
- Optical aberrations.

**❖ Computational Light Microscopy:**

1. **Indirect Imaging Scheme:**

- Computational light microscopy follows an indirect imaging scheme: "optical modulation, then image acquisition, and finally information demodulation."
- This approach aims to overcome the limitations of conventional microscopy.

2. **Hybrid Optical-Digital Mechanism:**

- Hardware components (illumination, optics, photodetector) and image processing algorithms are jointly designed and optimized.
- This integration creates a hybrid optical-digital microscopy mechanism.

**3. Enhancements:**

- Enables three-dimensional (3D) imaging.
- Decrease optical aberrations.
- Enhances resolution beyond diffraction limits.
- Allows for multispectral imaging.

**4. Optimized Design:**

- The joint optimization of hardware and algorithms allows for a more flexible and adaptable imaging system.

## 5- Multiple scattering

In the context of photon interactions with a sample, multiple scattering occurs when photons pass through a medium, they can interact with the particles within that medium, and these interactions can involve scattering. The scattered photons may not travel directly from the source to the instrument detector; instead, they may undergo multiple scattering events, changing direction each time they interact with a particle. This process can lead to a complex path for photons within the material.

Understanding and accounting for multiple scattering is crucial in various scientific and technical fields, such as **medical imaging, environmental monitoring, and materials science**. It introduces challenges in terms of accurately interpreting experimental data.

- Researchers often employ various techniques, including mathematical modeling and correction algorithms, to account for the impact of multiple scattering and obtain useful information from measurements.

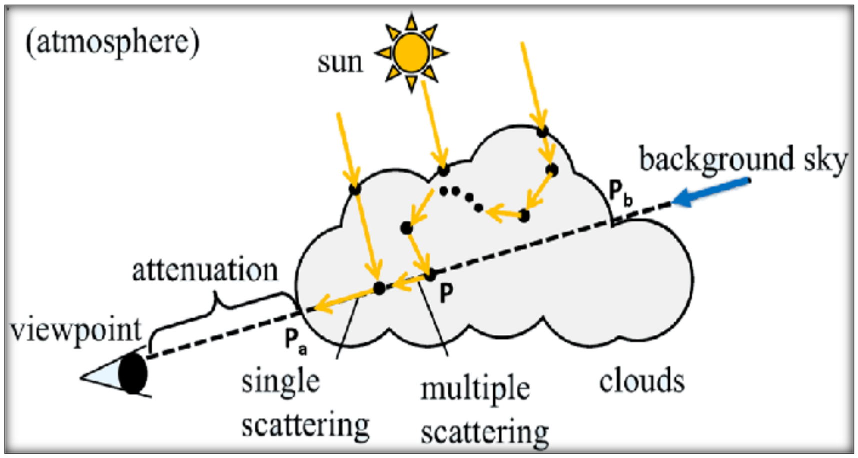
## Symptoms of the presence of multiple scattering:

(1) Multiple scattering can lead to a decrease in the measured amplitude, making it challenging to accurately determine the size of the scattering particles. This effect is often observed at higher concentrations where multiple scattering events become more spread.

(2) The apparent size of particles or structures in a sample, as determined by light scattering techniques, may decrease at higher concentrations due to the impact of multiple scattering.

(3) Polydispersity refers to the distribution of particle sizes within a sample. Multiple scattering can introduce additional complexity and variability in the observed scattering pattern, leading to an apparent increase in polydispersity, especially at higher concentrations.

❖ The effects of multiple scattering can be minimized by shortening the path length between the scattering center and the detector this lead to making the interpretation of experimental data more clear.




## 6-Diffusion approximation

The diffusion approximation is a simplified mathematical model used to describe the behavior of particle transport, heat conduction, or other diffusive processes. It is often applied to situations where particles or energy move randomly, undergoing multiple scattering events.

Diffusion equation is commonly written as:

where:

$$\frac{\partial \phi}{\partial t} = D\,\frac{\partial^2 \phi}{\partial x^2}$$

- which is a partial differential equation describing the spatial and temporal evolution of a diffusing quantity.

- $\phi$ is the diffusing quantity (e.g., concentration, temperature).
- $t$ is time,

- ***x*** is spatial coordinate, indicating the position in space where the diffusing quantity is being observed.
- ***D*** is the diffusion coefficient, representing how fast the quantity diffuses through the medium.

## 7- Imaging in turbid media

As light travels through turbid media, it encounters particles or structures that scatter and absorb the light. where used continuous-wave laser, in order to match the coherence length between the dynamic object wave and the reference wave. A camera or imaging device captures the scattered light that makes it through the turbid medium. Special techniques or algorithms are used to process the captured image. These methods help enhance visibility and reduce the impact of scattering, making the objects within the turbid medium clearer. To solve the problem of difficult focusing in imaging through turbid media an autofocus technology is applied. Spatial filtering techniques may be used to boost image contrast, making objects stand out more clearly against the turbid background. In some cases, digital holography might be used. This technique captures both the amplitude and phase of light, providing additional information for reconstructing a three-dimensional image.

When a laser beam illuminate turbid media, it divides into a **ballistic component, a snake component, and a diffusive component**, as shown in figure.

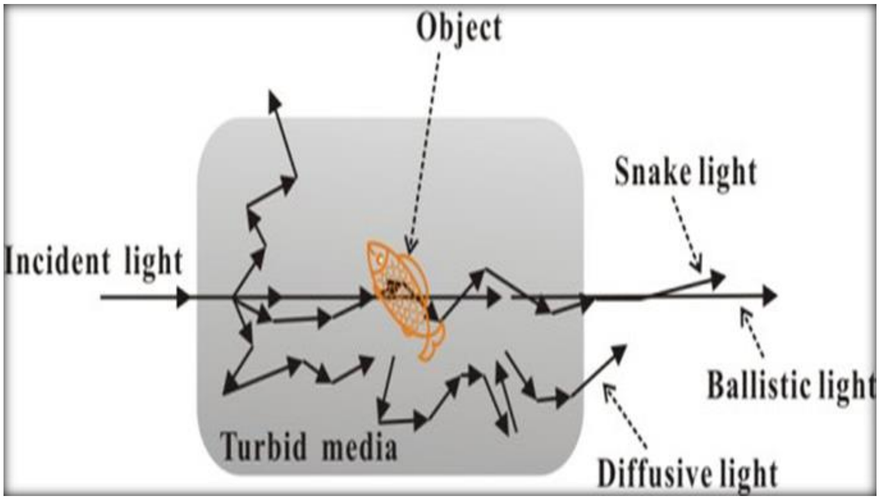



**Figure: Light propagation in turbid media.**

a. The ballistic photons propagate in straight lines and take the shortest path through the media. The coherence properties of ballistic photons are maintained.
b. The snake photons refract and propagate in a small taper angle and take relatively short paths through the media. The snake photons are quasi-coherent.
c. The diffusive photons are multiply scattered and travel over a much larger distance in the media than the ballistic photons or snake photons do. The diffusive photons are incoherent.

- If an object is embedded in a turbid medium, the ballistic photons and snake photons will contain image information of the object, and the diffusive photons will lose most of the image information and only contribute to noise. Therefore, to image the object in a turbid medium, we should selectively detect the ballistic photons and snake photons and reject the diffusive photons.

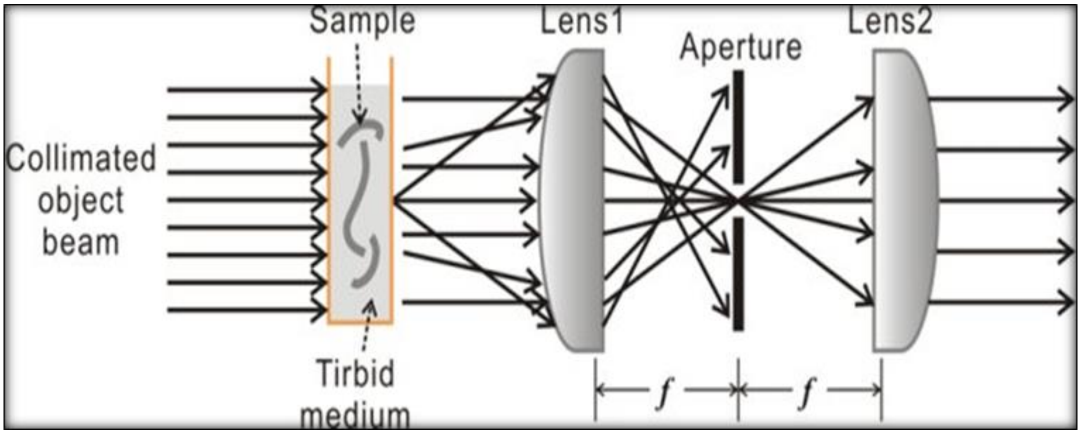



Figure: Schematic diagram of collimated beam propagating through turbid medium and spatial filter.

A spatial filter, shown in above figure, is set in the recording light path. An aperture is placed at the focal plane between the two lenses. When a collimated beam illuminates an object embedded in a turbid medium, the emergent ballistic photons and snake photons will travel parallel or approximate parallel to the incident direction, while the diffusive photons will greatly deviate from the direction of incident light. So only the ballistic photons and snake photons will be focused near the focal point of the first lens and pass through the small aperture. The diffusive photons will be blocked by the small aperture. With the spatial filtering technique, the scattered noise can be reduced. Ultimately, imaging in turbid media is of particular interest in fields such as biomedical imaging, where the goal is to monitor tissues or organs within the human body, even when they cannot be accessed directly.