Biomedical Imaging & Analysis

Lecture 2, Part 1. Fall 2014

Image Formation & Visualization (I): ***MRI & k-Space***

*[**Text**:* Joseph P. Hornak, *The Basics of MRI*

http://www.cis.rit.edu/htbooks/mri/inside.htm]

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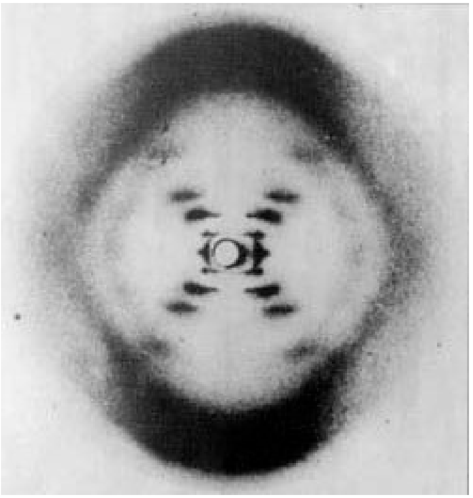
How is the course organized

- Image **Formation**
- **Basic** Image Processing
  - Linear filtering
  - Singular Value Decomposition & Image Compression (Gilbert Strang)
  - Invariance
  - Applications in Machine Vision & Feature Extraction
  - Feature Classification
- **Advanced** Image Processing Topics
  - Shape Analysis, Registration, Mutual Information
  - Optical Flow & Physics based image processing / Regularization
  - Shape and Appearance Models

Image **Formation** & **Visualization**

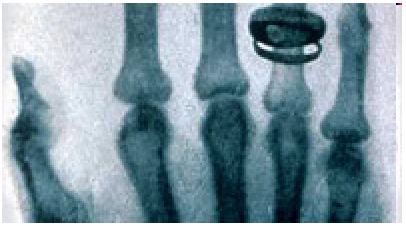
- System’s model of an Imaging Device.
- Noise formation and propagation.
- Signal to Noise v/s Contrast to Noise
  - Image bit depth
  - Windowing & Leveling
- Software for Image Visualization
  - ImageJ, ITK-SNAP, Paraview
- Physics of Imaging
  - X-ray & CT
    - Tomographic Reconstruction Techniques
  - Fluoroscopy
  - MRI
  - Optical Imaging
    - Resolution limits
    - Point Spread Functions

Biomedical Imaging == Medical images + Biological Images

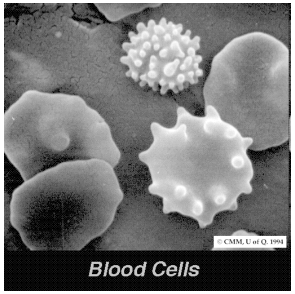


Data: Rosalind Franklyn

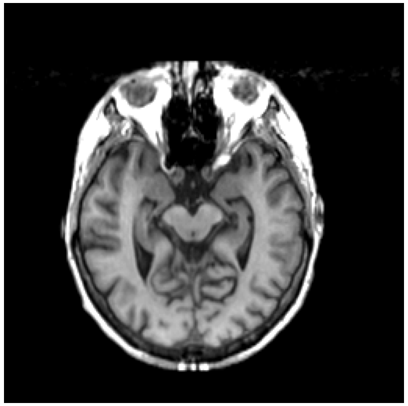
X-ray diffraction image of DNA crystals
Watson, Crick, Wilkins (Nobel 1962)



X-ray image of the hand
Röntgen (1901) / Cormack & Hounsfield (1979)



Electron microscopy of red blood cells
Ruska (1986)



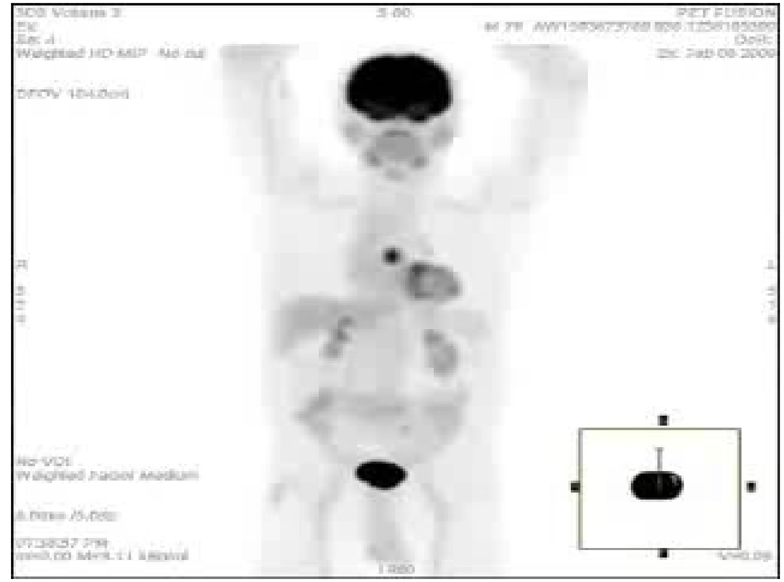
MRI of a head
Lauterbur / Mansfield (2003)

Biological vs Medical Imaging

- **Different modalities**
    - Bioimaging - mostly cellular and molecular level.
    - Medical imaging - mostly tissue and organ level
- **Different techniques & objectives**; Some shared principles
    - Medical image analysis is technically more mature.
- There is a growing trend of **convergence of these objectives**
    - E.g. molecular imaging using MRI with SPIOs…

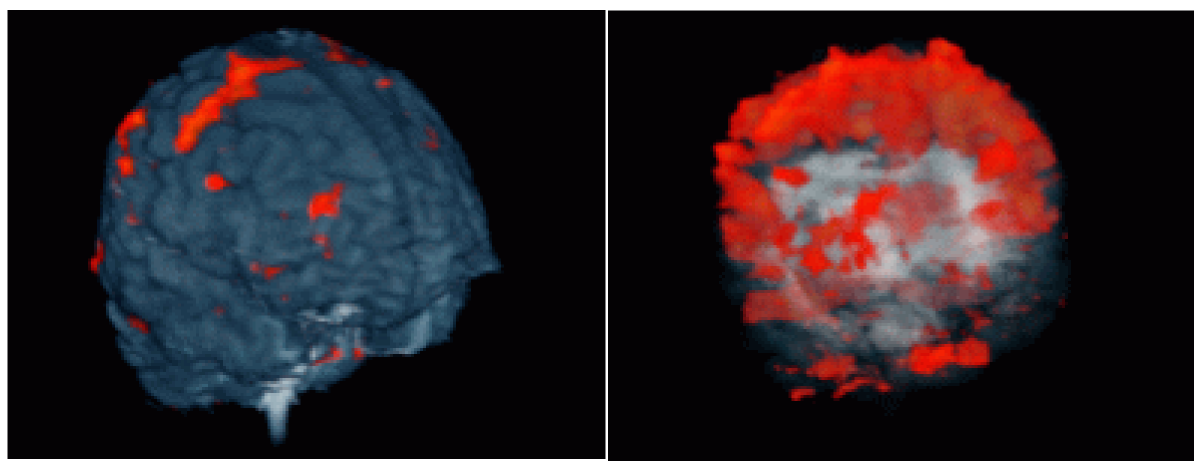
Examples of Medical Imaging

3D rendering of tumor for surgical planning (MRI)



Tumor Metastasis localization (PET)

fMRI of whole brain activation :

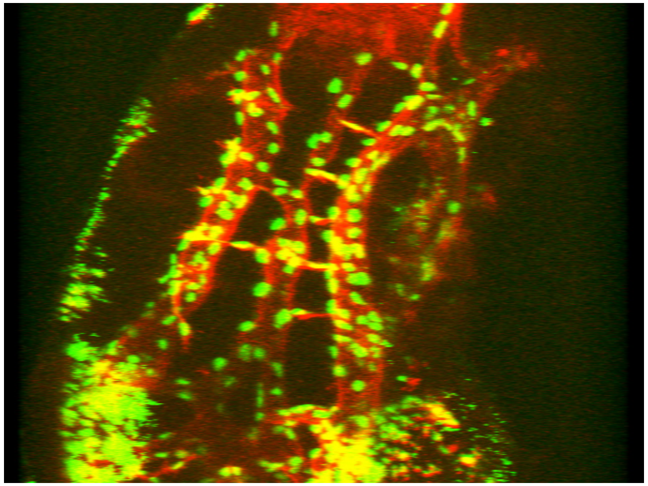


http://nobelprize.org/educational_games/physics/imaginglife/narratives.html

Examples of Biological Imaging

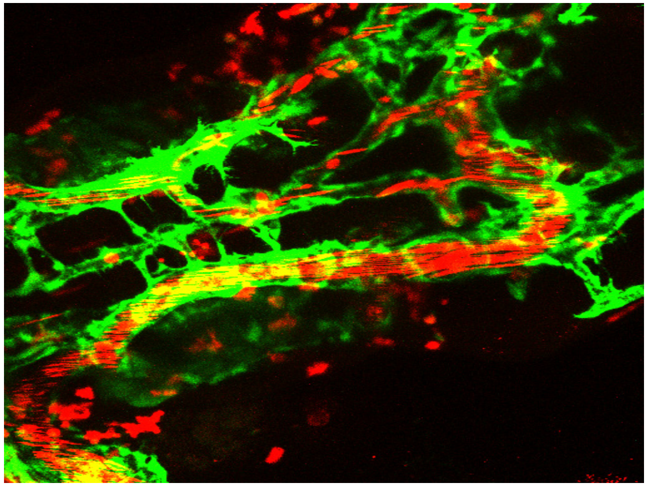
Instantaneous 3D

Confocal Microscopy



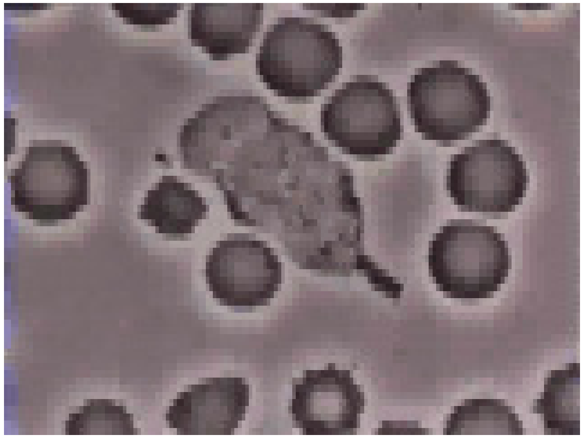
4D Confocal Microscopy

(3D + time)



^--- ZebraFish Vasculature: Fluorescent Epithelial Cell Nuclei, Filaments and RBCs.

Light Microscopy
(2D + time)



Life Sciences are unthinkable without Imaging: Assessment of biological processes with minimal perturbation of the system

Medical Image Formation: Ultrasound, CT & MRI

Topic (*total*: 3-4 lectures)	***Contents***
Introduction	Signal to Noise v/s Contrast to Noise – equivalents of resolution limits. *Electrical* Imaging Ultrasound imaging Basis of x-ray imaging Interactions of photons with matter/Radioprotection
X-ray imaging	X-ray imaging (fluoroscopy & computed tomography) Tomographic Reconstruction & Filtered Back Projection. Emission computed tomography (SPECT) Positron emission tomography (PET) Contrast agents & Tracer dynamics
Magnetic resonance I Basics	Basis of magnetic resonance effect T_1 and T_2 relaxation Spectroscopy Echo formation
Magnetic resonance II Advanced topics and contrast mechanisms	Elements of image formation – More Pulse Sequences fMRI: Biophysics of BOLD Contrast agents for MRI Diffusion tensor imaging

Biological Image Formation: Optical Systems

Topic (*total*: 1-2 lectures)	***Contents***
Introduction	Light Microscopy : basic image formation principles. System's model of an Optical System. Optical Resolution – Rayleigh Limit
Microscopy	Sources of Noise + System's modeling of noise Fluorescence Microscopy Bit depth and image storage Optimizing optical image formation – the Nyquist sampling limit.
Other Optical Imaging Methods	Practical constraints of light microscopy Optical Coherence Tomography
Advanced topics	Breaking the Rayleigh Limit: - Super-resolution - Confocal Microscopy

Pixels, Voxels, Contrast and Resolution

Imaging:

Localized measurement of a **contrast generating** biophysical effect in body/organ of living system

- What is measured:
  - Pixels
  - Voxels
  - Noise – affect Contrast

- 2D Image=nxm matrix of **pixels**

  Pixel = picture element

  Image **stack** = set of 2D images representing a volume.

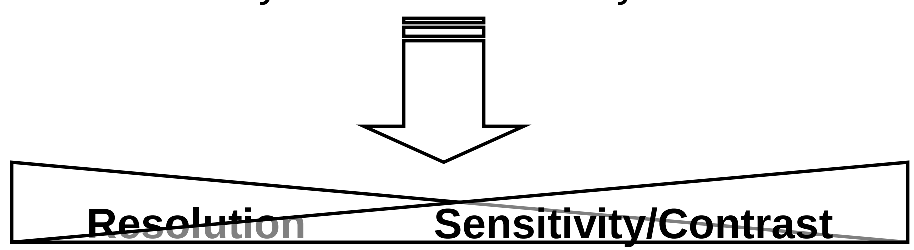
- 3D image=kxnxm matrix of **voxels**

  Voxel = volume element.

What is Contrast ?

- *Contrast* = difference in signal between tissues one wishes to distinguish or 'resolve', in a given image.
- Contrast-to-noise – Ability to distinguish tissue features against noise.

Increased resolution comes at the price of decreased contrast and therefore sensitivity to detection of tiny features:



Signal-to-noise v/s **Contrast**-to-noise

- Signal-to-noise ratio (SNR)
- SNR provides a means to estimate the precision with which the signal S is measured
  - S: signal (or measurement variable)
  - σ: standard deviation of its measurement

$$SNR = \frac{S}{\sigma}$$

When is it is possible to have excellent SNR but poor CNR ..?

To discriminate two signals S_1 and S_2 we need more than just good signal to noise ratio. The ability to discriminate the two is assessed using the contrast to noise ratio…

Contrast-to-noise ratio (CNR)

S_1 and S_2 : two signals (or measurement variable) of two different tissues,

σ : standard deviation of their independent measurement (assumed here to be identical and statistically independent)

$$CNR = \frac{S_1 - S_2}{\sigma}$$

CNR provides a means to estimate the precision with which S_1 can be discriminated from S_2

Optimizing SNR

- It is possible to optimize SNR by performing N repeated measurements S_i.
- Eg: 4 measurements improve the precision by two-fold.
- The precision of the average $\langle S\rangle=\sum S_i/N$ depends on the square root law

  - $S_i=S+\varepsilon_i$

  - where $\langle\varepsilon_i^2\rangle=\sigma^2$, $\langle\varepsilon_i\rangle=0$.

If S is the true signal (unknown):

- $\langle S\rangle=\sum S_i/N=S+\sum \varepsilon_i/N$

$$\Delta S \equiv \langle S\rangle - S = \frac{\sum \varepsilon_i}{N} \qquad \Delta S^2 = \frac{\left(\sum \varepsilon_i\right)^2}{N^2}$$

$$\Delta S^2 = \frac{\left(\sum \varepsilon_i^{\,2}\right)}{N^2} + \frac{\overbrace{\left(\sum_{i\neq j} \varepsilon_i \varepsilon_j\right)}^{\langle\varepsilon_i\varepsilon_j\rangle=0,\ i\neq j}}{N^2}$$

$$\left\langle \Delta S^2 \right\rangle = \frac{\sum \left\langle \varepsilon_i^{\,2} \right\rangle}{N^2} = \frac{N\sigma^2}{N^2} = \frac{\sigma^2}{N}$$

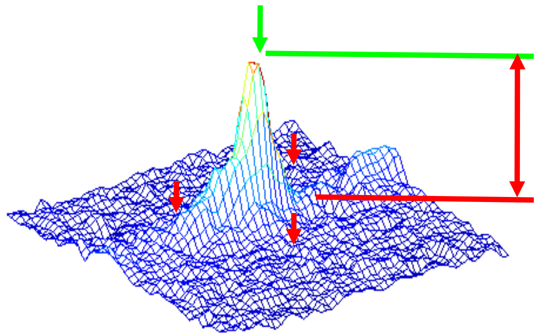
$$\boxed{\left\langle \Delta S \right\rangle = \frac{\sigma}{\sqrt{N}}}$$

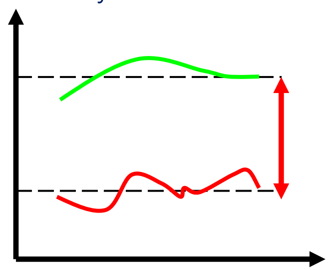
The Problem..?

- Results in increased measurement time.

Slide adapted from EPFL, Fund BioImag 2013

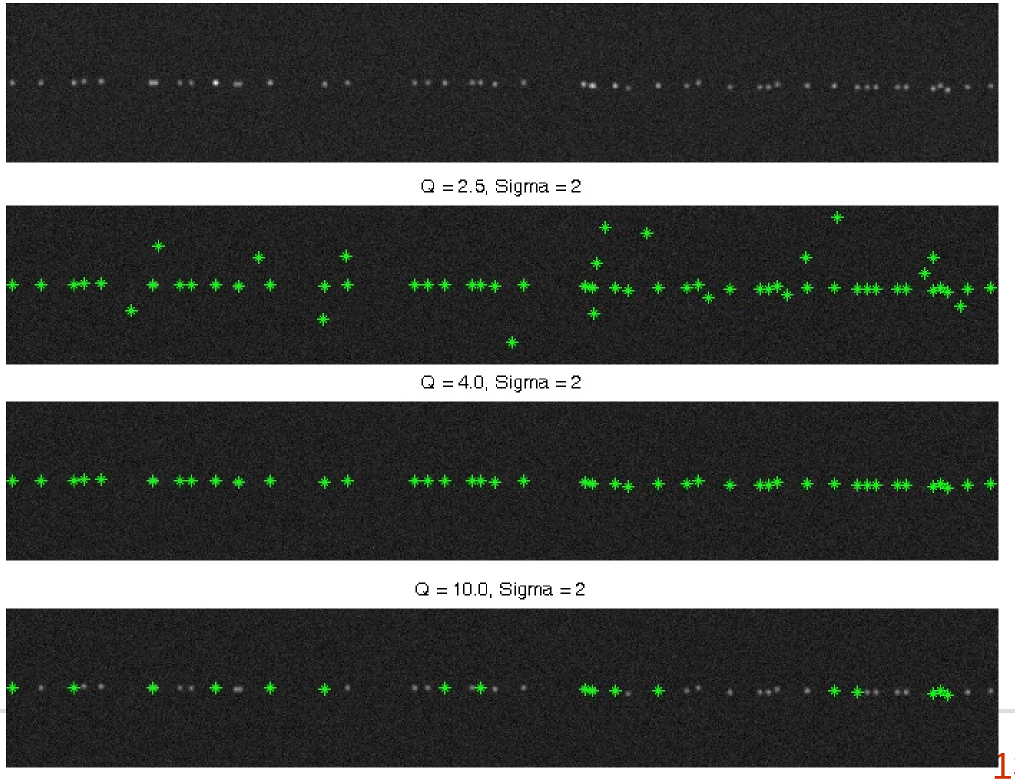
Statistical Selection of Features





$$I_{max} - I_{BG} \geq Q \cdot \sigma_{\Delta I} ?$$

Q: selection quantile



Optimizing CNR ?

•Optimizing contrast = choice of experimental parameters (e.g. protocol) to maximize the difference in two tissue signals S_1 and S_2.

complex and empirical procedure

some effects can be predicted/calculated, if the signal behavior can be modeled.

Error propagation calculation

Let the signal S be a function S(k,t)

k is a tissue property (signal decay rate)

t an experimental parameter (such as time).

Approach:

1. Determine dS/dk
2. Find t_0 where dS/dk is maximal by taking derivative rel. to t

Example: $S(k,t) = S_0 e^{-kt}$

$$\frac{dS(k,t)}{dk} = -S_0 t e^{-kt}$$

Maximum is where derivative with respect to t is zero

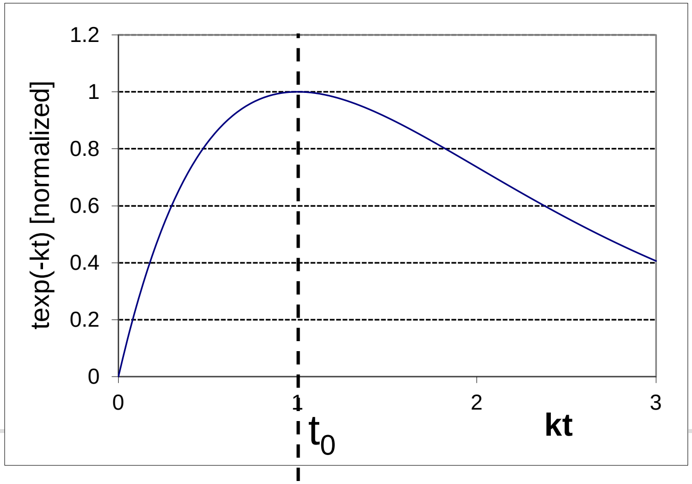
$$\frac{d}{dt}\left(-S_0 t e^{-kt}\right) = 0$$

$$= -S_0 e^{-kt} + S_0 k t e^{-kt}$$

$$= -S_0 e^{-kt} \underbrace{(1-kt)}_{\boxed{t_0 = 1/k}} \mathbf{=0}$$

For an exponentially decaying signal, the optimal time of measurement is equal to 1/decay rate

How critical is the choice of t_0 ?

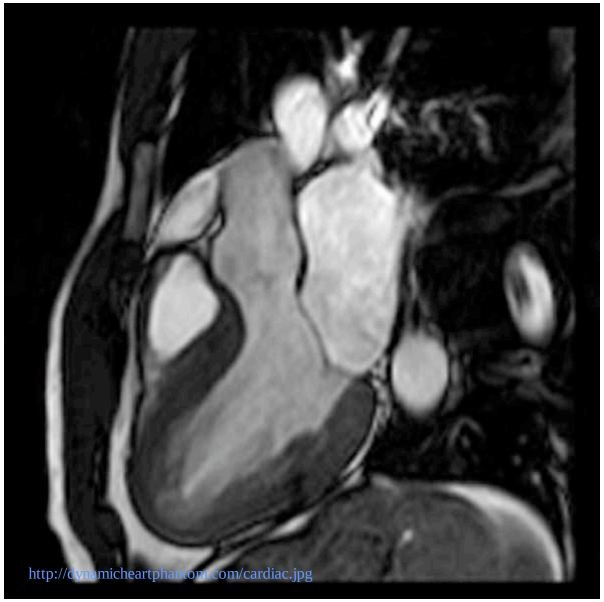


Slide adapted from EPFL, Fund BioImag 2013

Physics of Imaging

- Multiple aspects of imaging are influenced by physics
  - Signal Source
  - Contrast generation
  - Motion compensation/tracking
  - Blood flow
  - Artifacts
  - Image generation
  - Field of view
  - Tissue heating
  - Radiation
  - Intervention options
  - Limiting factors
  - …

MRI: Physics meets Clinic (Part I)

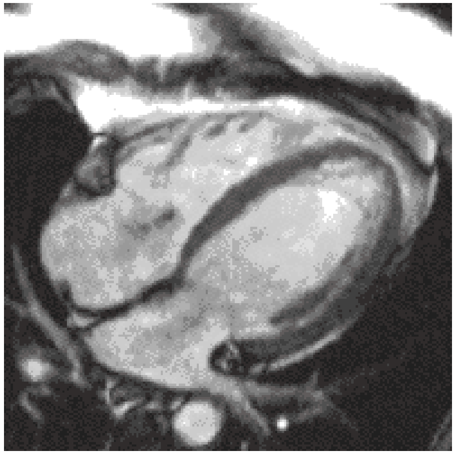


Working Principles:

- Nuclear Magnetic Resonance (NMR): Magnetism , precession of magnetic moments.
- Nuclear magnetic fields moments: Essentially all MRI is hydrogen (proton) imaging.
- Spin orientation and spin state transitions & Larmor frequency. For most atoms, the net nuclear spin is zero.

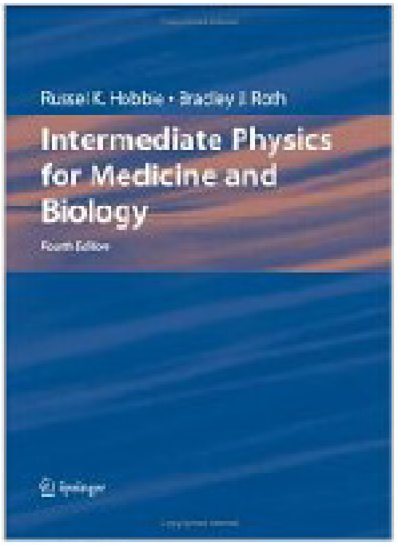
Pulse Sequences:

- RF pulses & NMR signal
- T1 & T2 relaxation
- Spin echo formation
- Contrast mechanisms
- MRI scanners and imaging



References

- Joseph P. Hornak, *The Basics of MRI*
  - http://www.cis.rit.edu/htbooks/mri/
- Online MRI simulator (brainweb)
  - http://www.bic.mni.mcgill.ca/brainweb/
- Hobbie, Roth, *Intermediate physics for medicine and biology*.



History

- Block, Purcell (Nobel prize winners 1952) credited with discovering nuclear magnetic resonance (NMR) phenomenon in 1946.
- Between 1950~1970, NMR was used mostly in chemical and molecular analysis.
- In 1973 P. Lauterbur (Nobel prize 2003) demonstrated MRI on test tube samples.

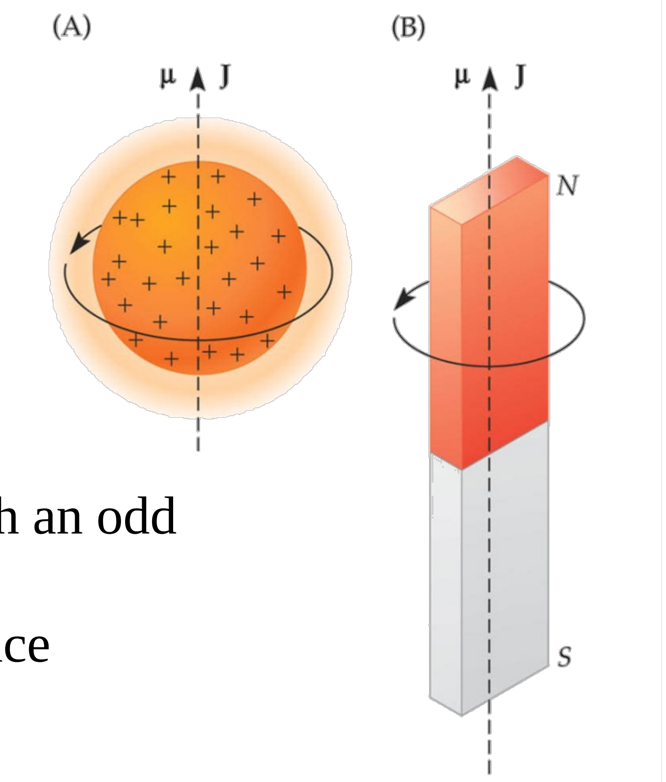
MRI: Physics meets Clinic (Part I)

What kinds of nuclei can be used for NMR?

- Protons & neutrons are filled in nuclear orbitals by spin to minimize the nuclear energy. The nucleus has 2 properties:
  - Spin & Charge

- Nuclei are made of protons and neutrons
  - Both have spin ½
  - Protons have charge

- Pairs of spins tend to cancel, so only atoms with an odd number of protons or neutrons have spin :
  - Good nuclear choices for magnetic resonance are: ${}^{1}H_{1}$, ${}^{13}C_{6}$, ${}^{19}F_{9}$, ${}^{23}Na_{11}$, ${}^{31}P_{15}$



An Introduction to MRI Physics and Analysis ,Michael Jay Schillaci, PhD

- Hydrogen is the most abundant atom in the body (H_2O) and the majority of hydrogen is in water .

***MRI*: Physics meets Clinic (Part I)**

Working Principles…

Three main ideas:

1. Magnetic moments of unpaired protons or neutrons and their interaction with an applied magnetic field → **Nuclear Magnetic Interaction.**

2. A resonance is created in system (by an external RF source) and detection of the same by Faraday's law → **Resonance**

3. Mathematical reconstruction of an image → **Imaging**