Escola de verão CIBIT-ICNAS 2022

Ressonância Magnética: Estrutural e Funcional

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Overview

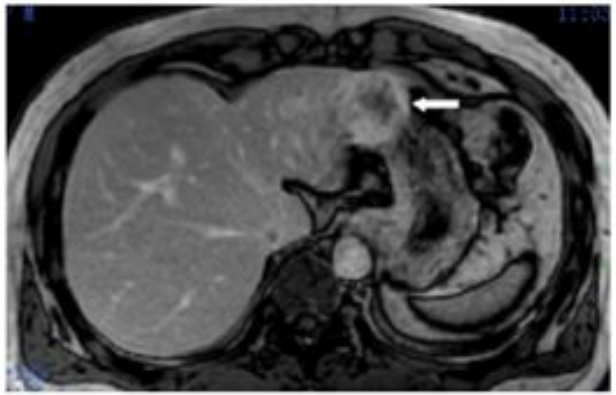
- Background
  - Medical imaging, basic concepts
- NMR signal
  - Relaxation
    - longitudinal and transverse
- From signal to image
  - Structure and function

Short bio

(2013-today) Post-doc with CIBIT. Involved in several projects - BrainTrain, NECSUS, Brainplayback, etc.
(2008-2013) PhD degree in Information Science and Technology | Faculty of Science and Technology of the University of Coimbra Thesis: *"Development of classification methods for real-time seizure prediction"*
(2007-2008) M.Sc. degree in Biomedical engineering | Faculty of Science and Technology of the University of Coimbra
(2002-2007) Licentiate degree in Biomedical engineering | Faculty of Science and Technology of the University of Coimbra

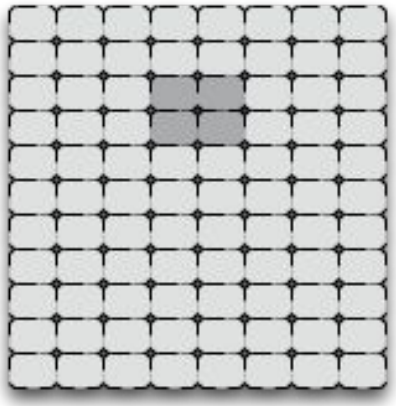
Overview

A 46-year-old male with hepatocellular carcinoma of the left lobe of liver. Contrast enhanced MR image ***shows a periphery enhanced mass*** *invading the stomach (...) (http://qims.amegroups.com/article/viewFile/1317/1773/4537)*



Keys to identify alterations?

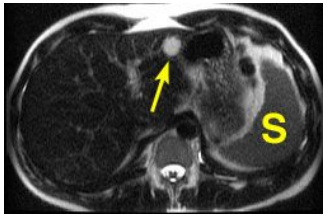
- ***Contrast*** *resolution*
- ***Spatial*** *resolution*

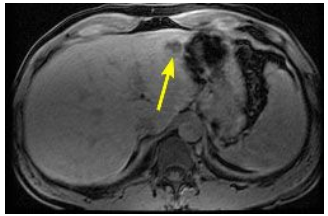


Overview

- To create an **image** we need a **signal - we will use the properties of the tissues generate and the concept of nuclear magnetic resonance**
  - We can change the nature of the image, changing specific parameters of MRI to improve the *contrast resolution* and *spatial resolution* of the image

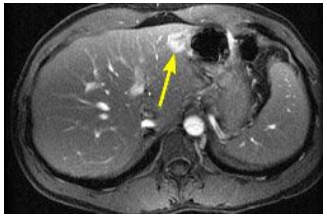
T2-weighted image





Un-enhanced T1-weighted

w/ contrast agent



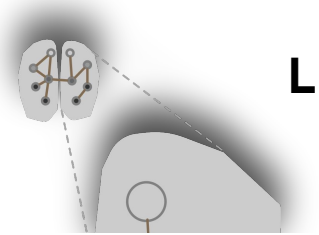
Imaging and the study of the brain

1861 — Tan tan
By Paul Broca
Non-fluent aphasic patient

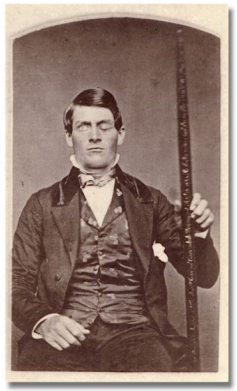
1868 — Phineas Gage
By John Harlow
Frontal lobe and related behaviours

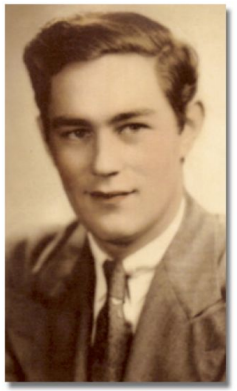
...

1957 — H.M
By W. Scoville
Bilateral medial temporal lobe removal and anterograde memory



Link between **brain trauma, damage** and **function impairment.**



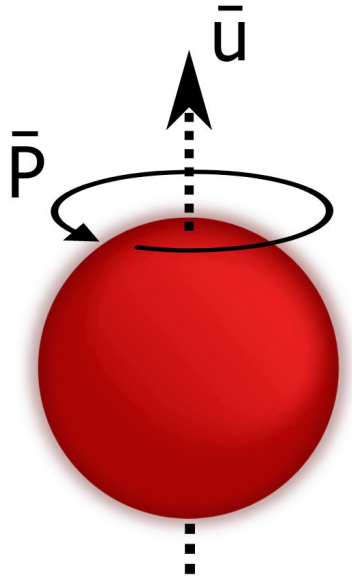


Phineas Gage, Louis Victor Leborgne (“tan tan”), Henry Molaison (H.M.)

Thiebaut De Schotten, M., Dell'Acqua, F., Ratiu, P., Leslie, A., Howells, H., Cabanis, E., et al. (2015). Cereb. Cortex 25, 4812–4827. doi:10.1093/cercor/bhv173.

From the basic element to the tissue

- The **atoms** that compose the human body have a **property known as spin**
  - a fundamental property of all atoms in nature like mass or charge
- Components of an atom such as protons, electrons and neutrons all have spin.
  - Angular moment (they precess)



Properties of the tissues
Magnetic susceptibility

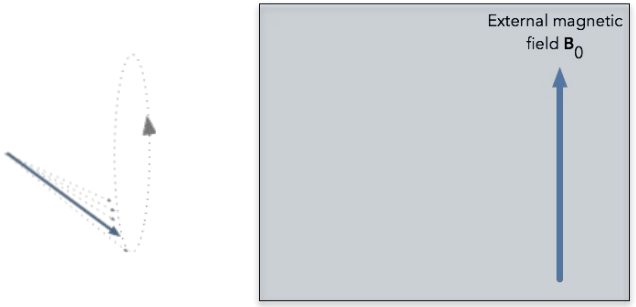
- Natural property of *all tissues*
  - **Measure of how magnetised the tissue becomes** when it is placed in a **strong magnetic field** (*depends on the arrangement of electrons in the tissue*)
    - ***Diamagnetic*** materials have a very weak susceptibility
      - Produces an internal field in the opposite direction to the applied field. *Most body tissues are diamagnetic*
    - ***Paramagnetic*** materials have a stronger susceptibility and produce a field in the same direction as the main field
      - examples include gadolinium (used as an *MR contrast agent*)
    - ***Superparamagnetic***
    - ***Ferromagnetic***

Take home message #1

- The MRI (image) is based on the **magnetic susceptibility** of the elements that are present in each tissue (‘magnetic properties of the tissues’).

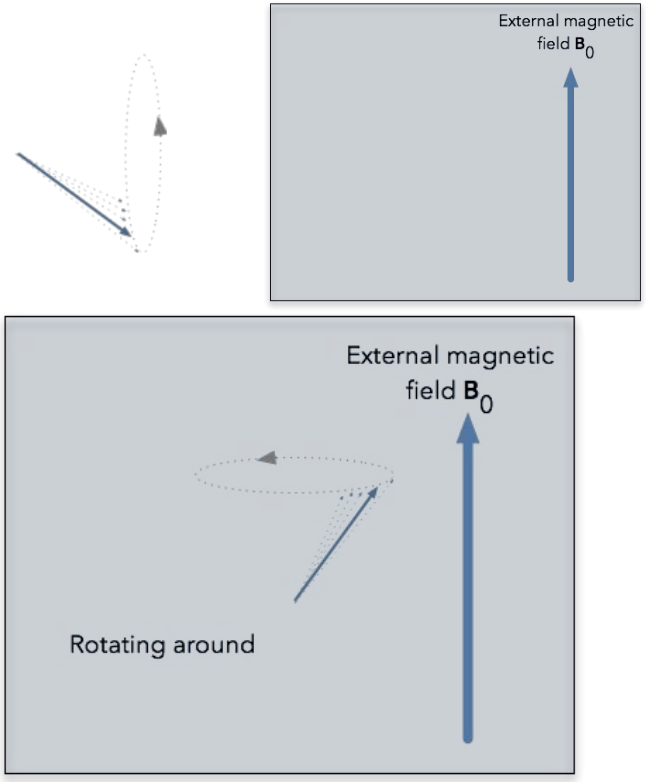
The compass problem

- What would happen if an **external magnetic B_0** field was **applied to this particle** (let say the Hydrogen proton)?



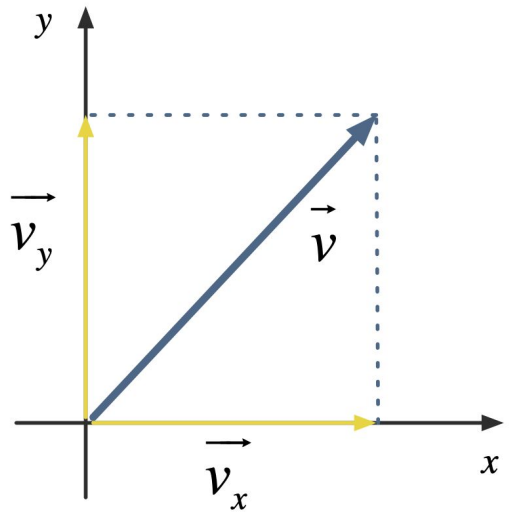
Generating the NMR signal

- What would happen if an external magnetic B_0 field was applied to this particle (let say the Hydrogen proton)?
  - We would *probably* expect an alignment with B_0
  - Reality, because of the *spin angular momentum*, it will rotate around B_0
    - **Precession**

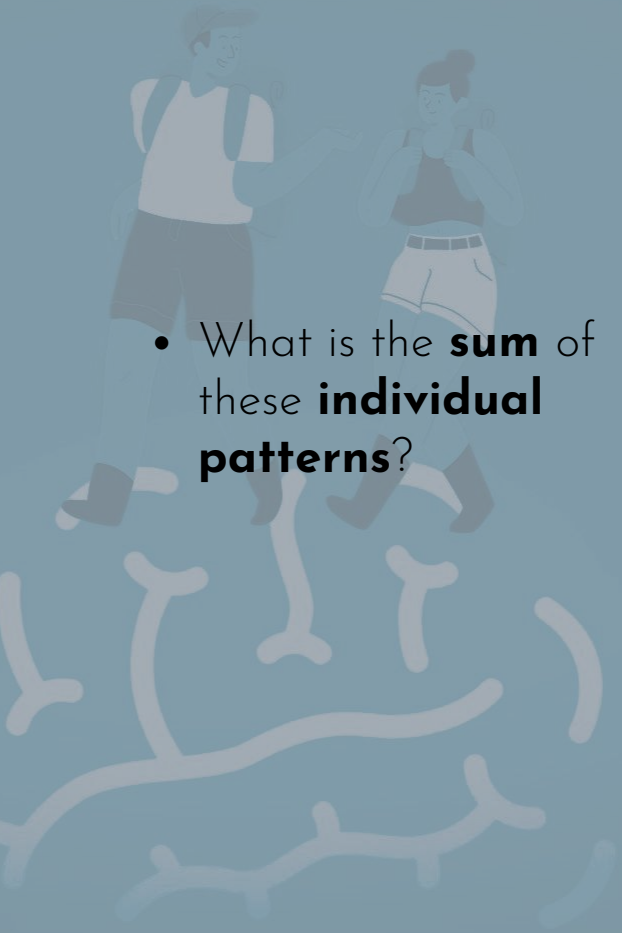


Mathematical side note

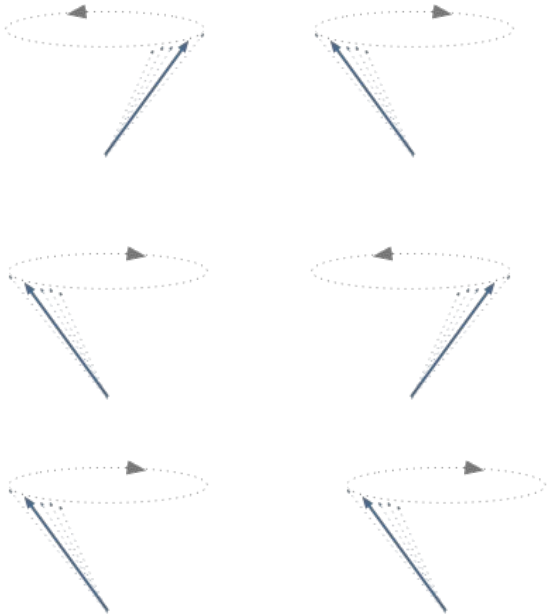
Vector ***amplitude*** and ***direction***
Vector decomposition into components (longitudinal and transverse)



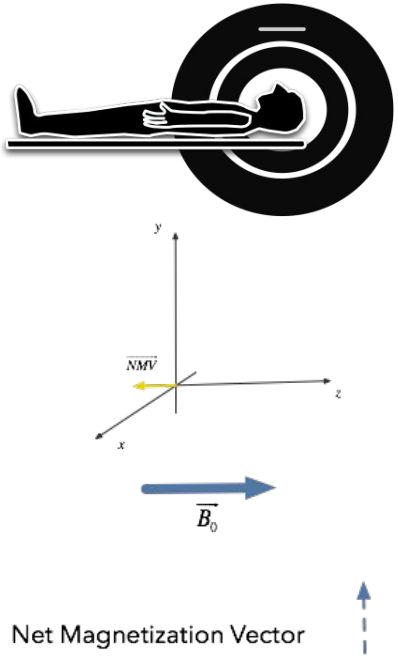
Net Magnetization Vector



- What is the **sum** of these **individual patterns**?



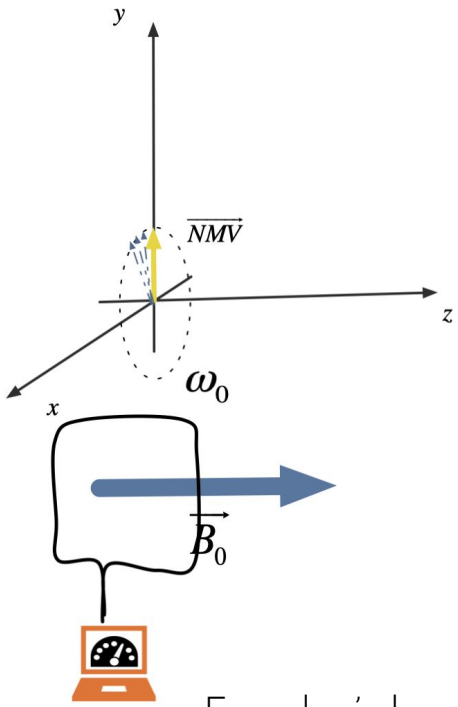
Generating the NMR signal



- We have a **Net magnetization vector** (NMV), antiparallel to B_0
  - we **cannot detect it** along the same direction of B_0 because of B_0 strength
- What **we want/need to do is to *change the orientation of the NMV***
  - *The **observable signal** is perpendicular* to the B_0
- Is it static (e.g. always pointing to the y-axis) ?

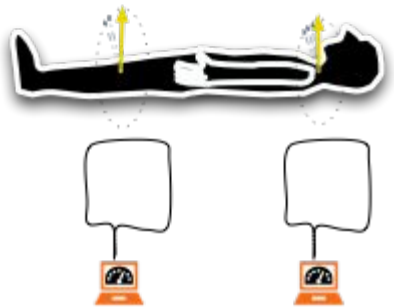
Hypothesis - **electrical induction using the transverse component**

- **Hypothesis**
  - **Longitudinal**
    - 'canceled', i.e. sum of all individuals is ~0
  - **Transverse** (if static we cannot measure it)
    - *precessing!* around z-axis/B_0
      - Larmor freq.
      - **Induces eletric currents**
  - Now the NMV can be detected!



Faraday's law of induction

Hypothesis - **electrical induction using the transverse component**

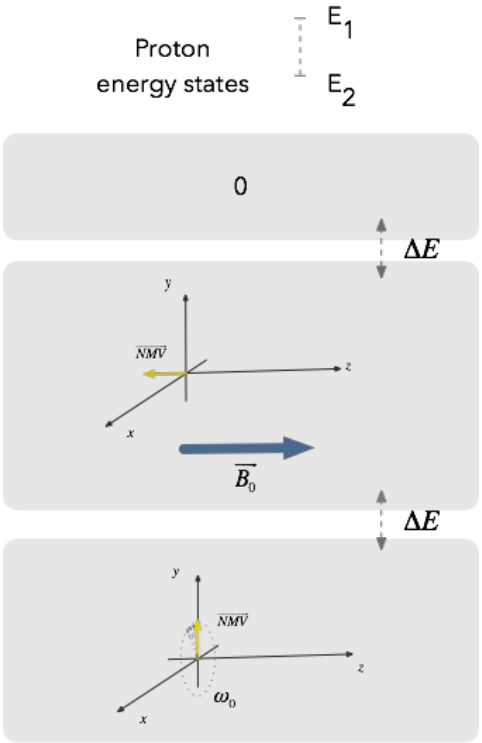


- **Transverse**
  - NMV is *rotating* around z-axis/B_0
    - Larmor freq.
  - The electrical induction (voltage generation) is proportional to the NMV
    - **Signal Intensity (as a measure of transverse magnetization)**
  - Different location with different NMV (transverse)

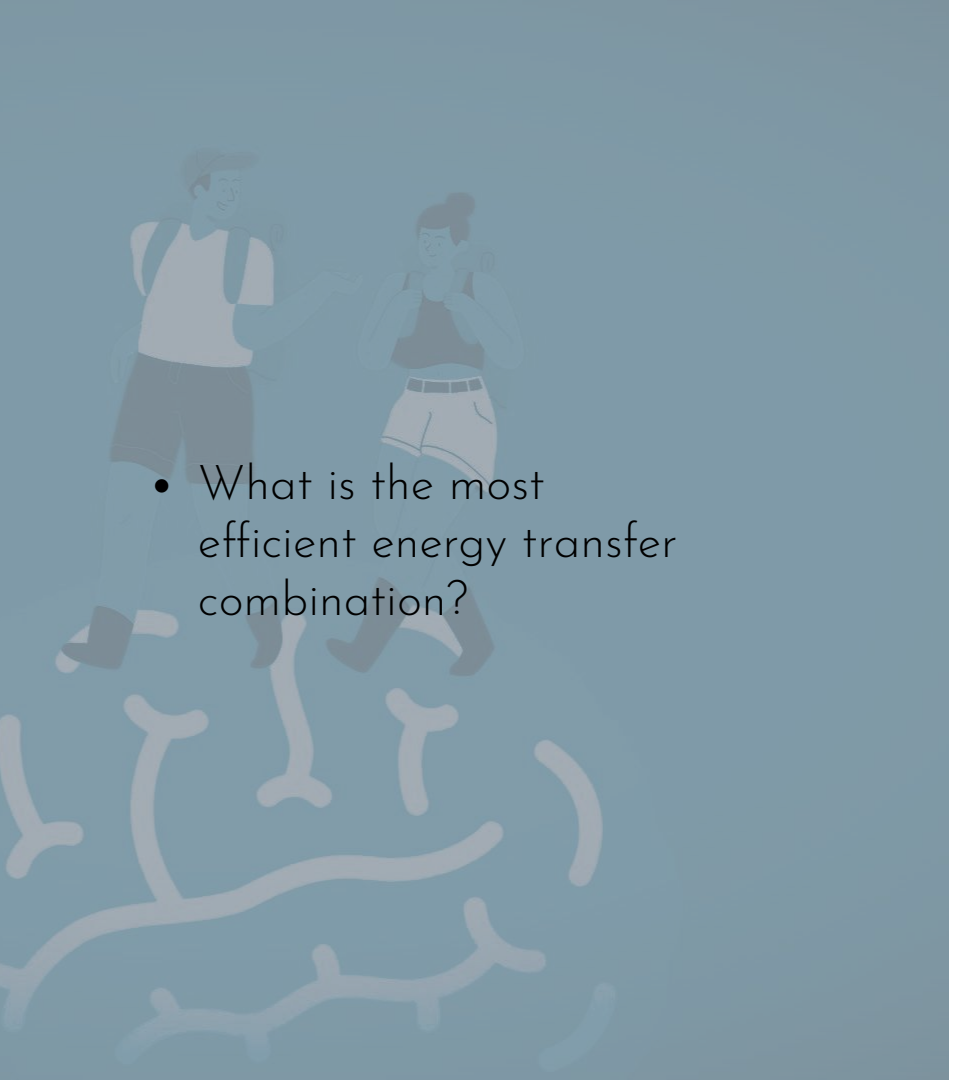
Take home message #2

- The net magnetization vector can be decomposed in two components: longitudinal and transverse.
- The transverse component preccesses around B0 and can be measured

Generating the NMR signal

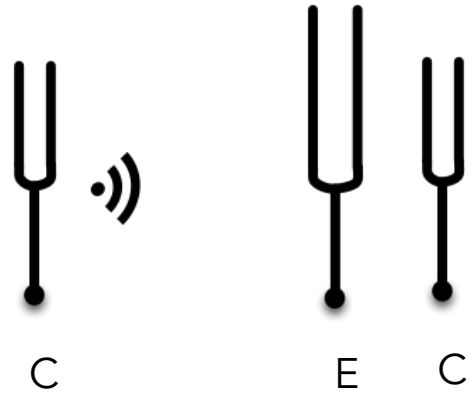


- How do we do this?
  - We need an additional 'system'
    - to get enough energy to provoke a change in NMV orientation



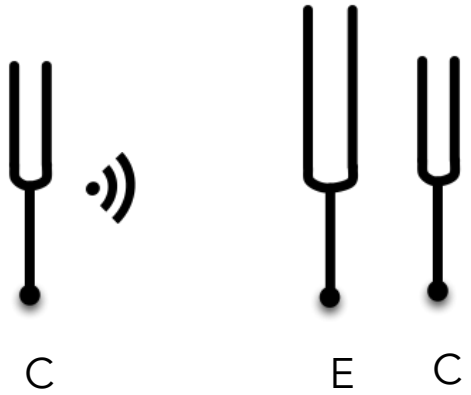
- What is the most efficient energy transfer combination?

Tuning forks



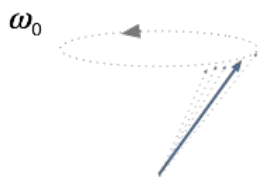
Resonance

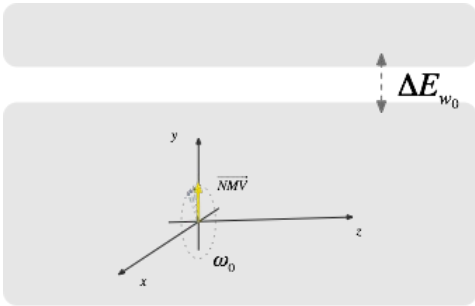
- Explore a feature named **Resonance**
  - Let us consider tuning forks (C or Dó and E or Mi)
  - If we hit the first C (on the left) it will start to oscillate/vibrate and the second C (on the right) will start to oscillate and the E will not!
    - due to the natural frequency at which the tuning fork oscillates
      - there is an **efficient transfer of energy** between both C's



Generating the NMR signal

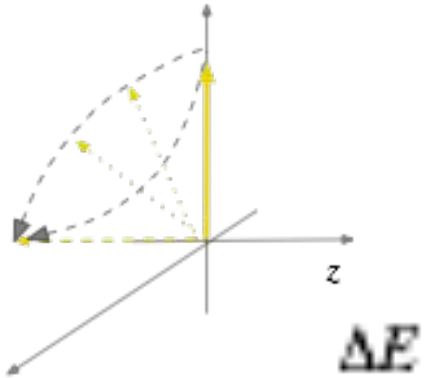
- Resonance in NMR
  - Precession, with frequency w_0, computed using the Larmor equation
  - If we apply energy in the system at this specific frequency
    - **we should have an efficient transfer of energy to the system**





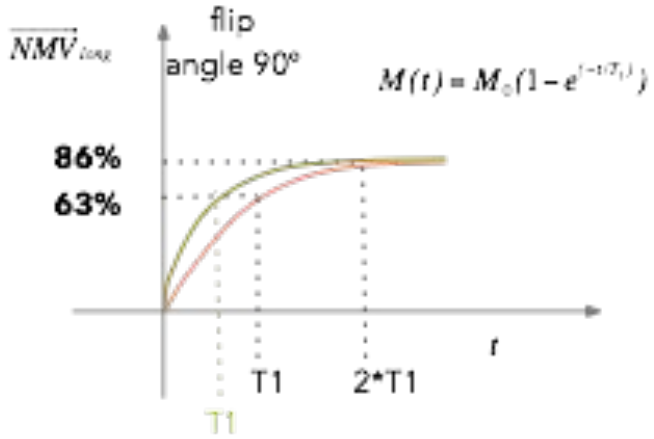
Relaxation

- Let us assume that B_1 is removed
  - **The system evolves to the lowest possible energy state**
  - end up in the resting state
    - **release of energy**
      - where does it goes?
  - Let's look at each part separately
    - **longitudinal and transversal**



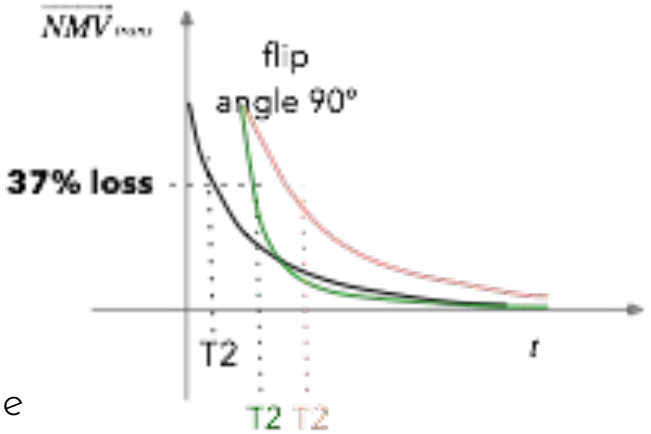
Longitudinal relaxation

- **Longitudinal** magnetisation (increase)
- a.k.a. spin-lattice relaxation
  - *lattice* - unrelated system elements
  - T1 increases with ↗**B**0
    - 63% of baseline longitudinal magnetisation



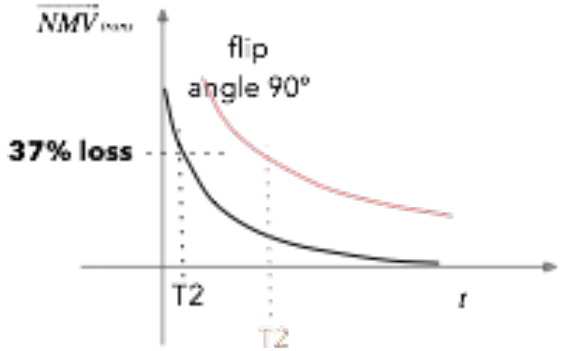
Transverse relaxation

- **Transverse** magnetisation (decreases)
  - exponencial decay
    - max when flip angle is 90°
  - how can we measure it?
    - the exponencial is described by a time constant called T2
      - amount of time that it takes to loose 37%



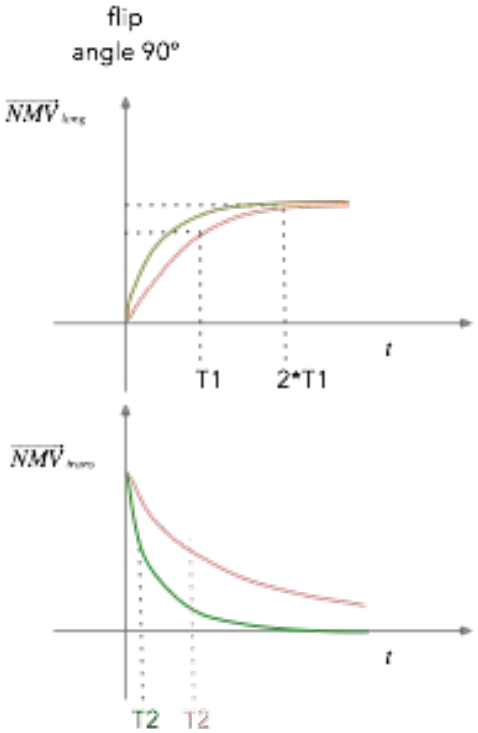
Transverse relaxation

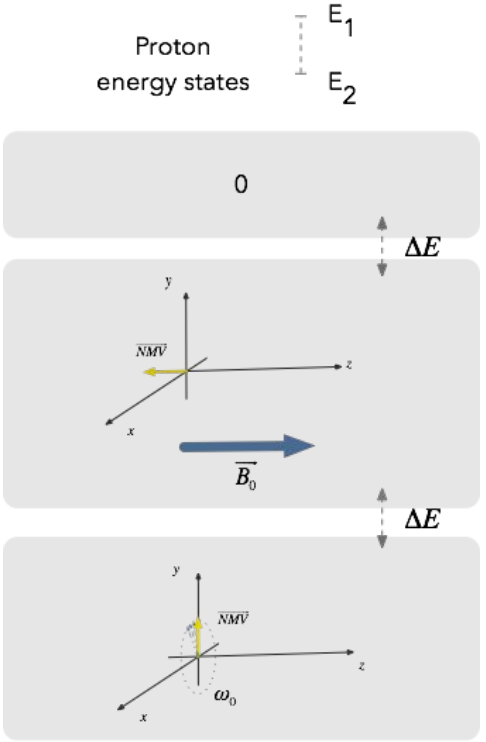
- **Energy transfer**
  - from spins (in higher energy state) to other spins
    - a.k.a. **Spin-Spin relaxation**
  - process **depends of energy exchange** between spins
- Example
  - (pink) e.g. CSF - longer T2
    - probability of energy exchange occurring is lower - spins are "far apart"



Longitudinal and Transverse relaxation

- Contrast between tissues
  - Look closer at the transverse/longitudinal magnetisation



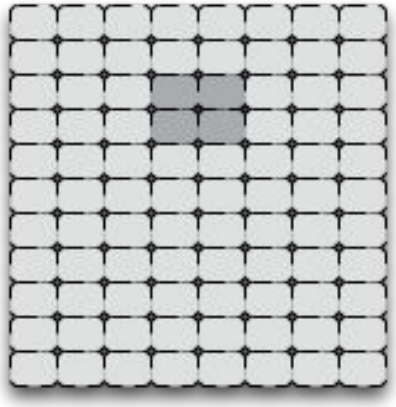


Take home message #3

- Longitudinal and transverse components relaxation patterns vary from tissue to tissue

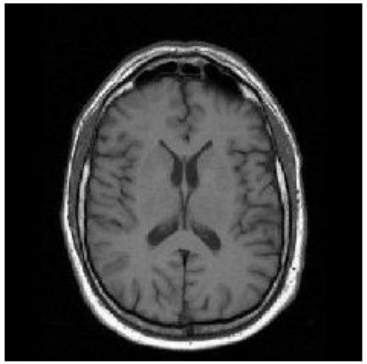
T1 vs T2

- As **imagens ponderadas em T1** vão ser **semelhantes às ponderadas em T2**?

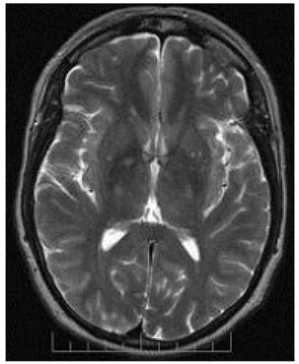


T1 vs T2 images

- Inversion in signal intensity
  - image with T1 contribution to the SI, higher spatial resolution
  - image with the T2 contribution, higher tissue contrast



T1 - Weighted

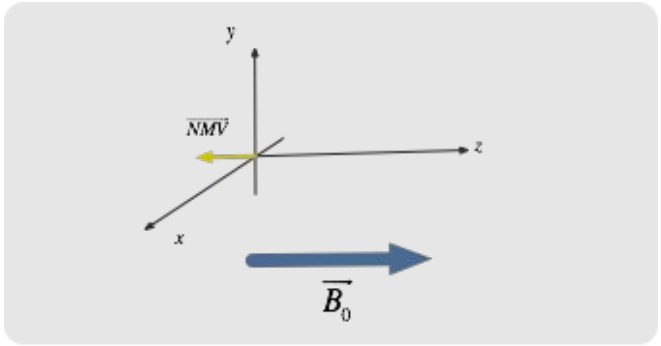


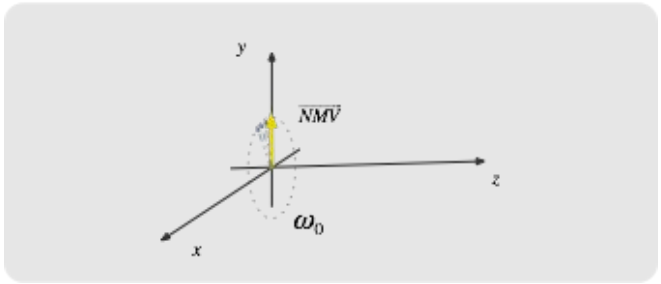
T2 - Weighted

Take home message #4

- We can **adjust specific parameters** and **pulse sequences** to produce different images
  - Structural images of the brain - ‘tissue’ encoded

Magnetic susceptibility





freq determined by the BO

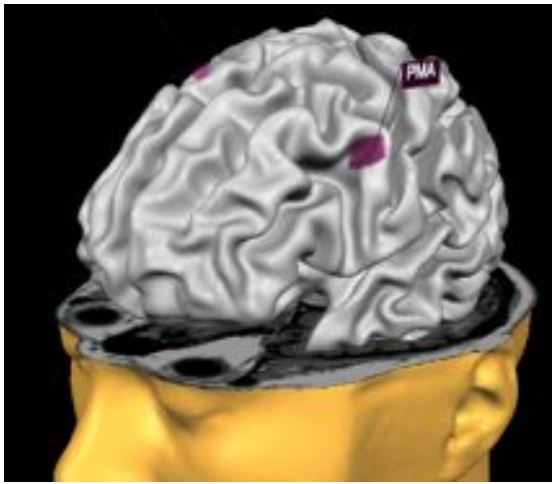
unfortunately, BO is not exactly the same throughout the entire body

interaction of tissues with the applied magnetic field BO causes point-to point variability - local amount of magnetic field (X)

$$\omega = \gamma(B_0 + X)$$

functional MRI

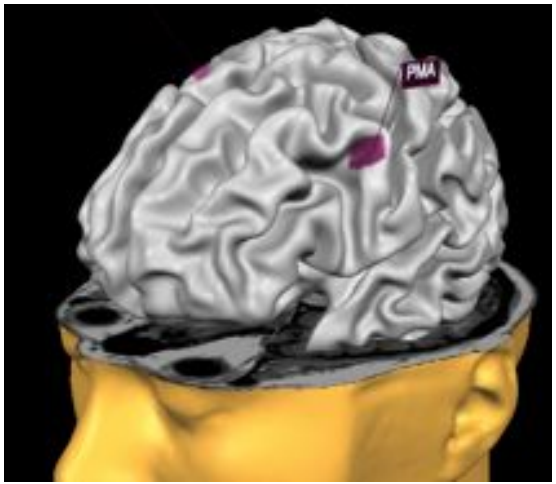
- How can we **use this** to study the **brain function**?



Brainvoyager Tutor

functional MRI

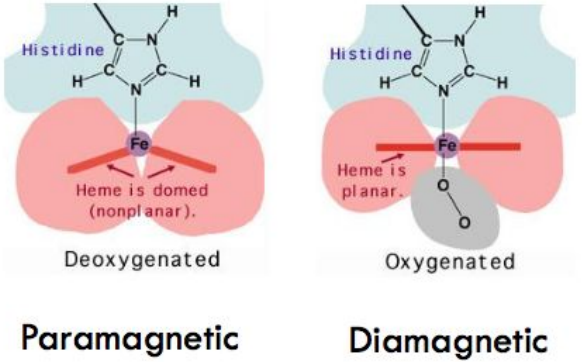
- Pre-operative tool (e.g. Epilepsy studies)
- The brain is *functionally* sub-specialized
  - brain regions related to/engaged specific tasks
  - increase in neuronal activity in these regions
    - the neurons require additional amount of metabolic substrates - vascular response
    - oxygen is delivered to cells bonded to *haemoglobin*



Brainvoyager Tutor

functional MRI - Background

- **Oxygenated** haemoglobin is **diamagnetic**
  - elements that have a very weak susceptibility
- **Deoxygenated** haemoglobin is **paramagnetic**
  - have a stronger susceptibility



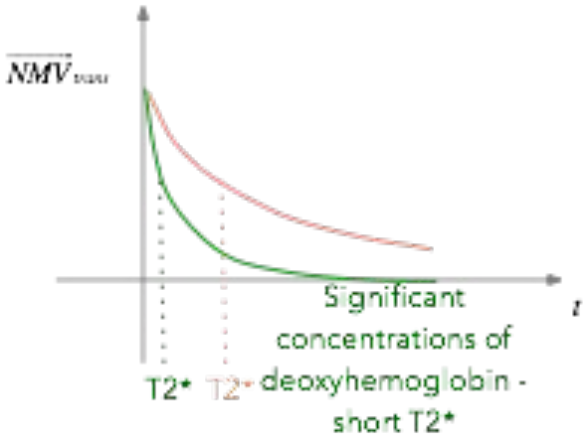
Paramagnetic

Diamagnetic

Take home message #5

- **Oxygenated** haemoglobin and **Deoxygenated** haemoglobin have different magnetic properties that influence its surroundings

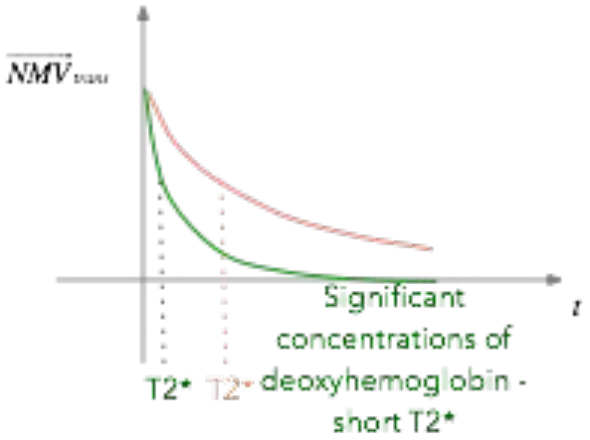
functional MRI - B.O.L.D.



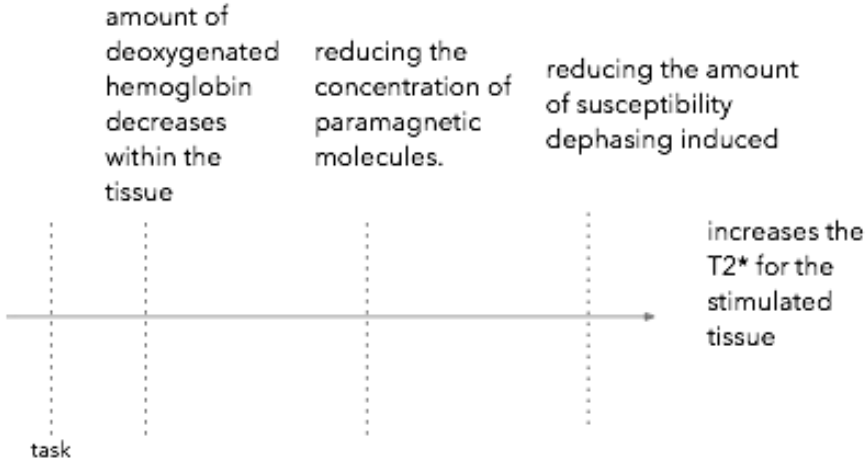
Significant concentrations of deoxygenated hemoglobin shorten **transverse** the *T2** relaxation time of the tissue

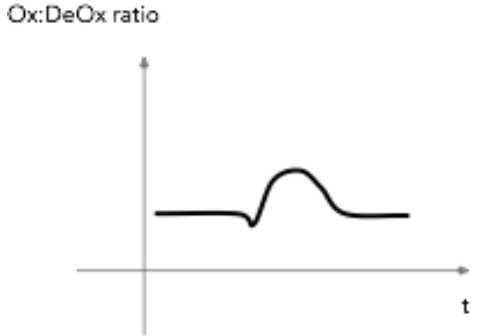
- decrease in SI compared to tissue with oxygenated haemoglobin.

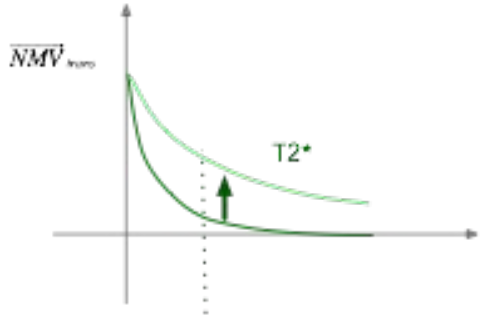
blood-oxygenation-level-dependent effect or BOLD effect



Let us assume that stimulated tissue - e.g. brain cortex engaged in a task -undergoes an increase in blood flow with an increased delivery of oxygenated haemoglobin



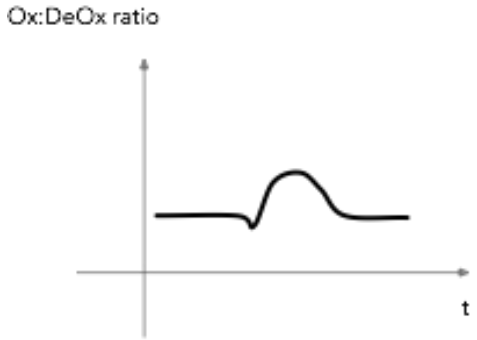




Haemodynamic response function

functional MRI - B.O.L.D.

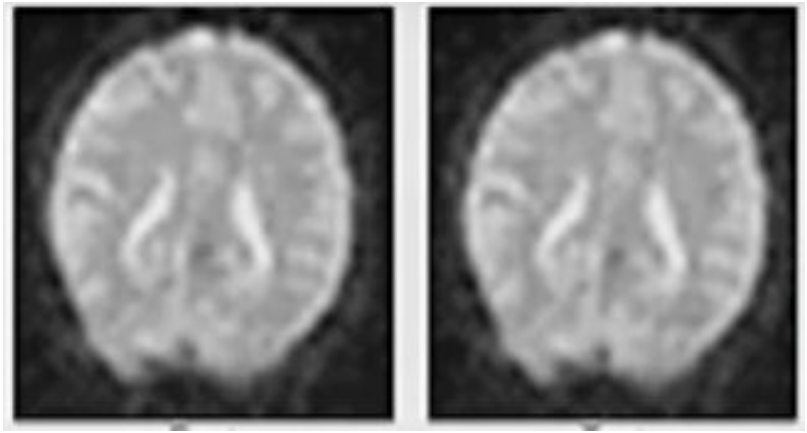
- How can we get an image based on this information?



- If enough resolution (contrast), we could determine which voxels change during task performance
  - delay after the beginning
  - very small signal change (2 to 3 % variation)

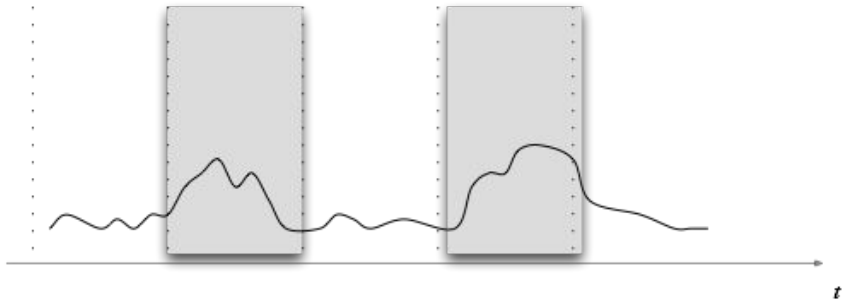
fMRI data

difference between two fMRI images



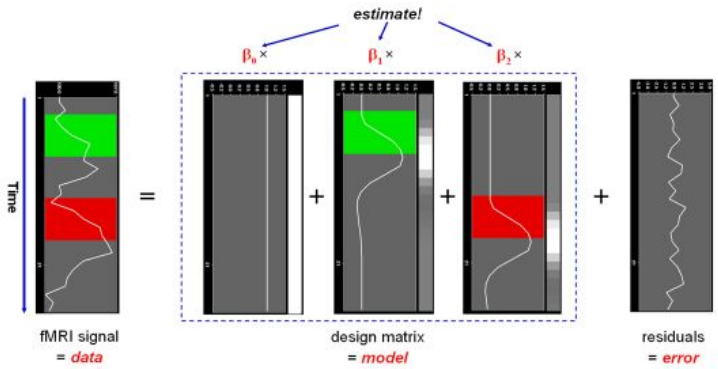
functional MRI

- The typical approach is to perform a large series of measurements in the presence and absence of the stimulus and subtract the images
  - increasing statistical significance



General Linear Model

- Statistical framework
  - Simplest case: baseline and condition
  - but we can go further and use different conditions

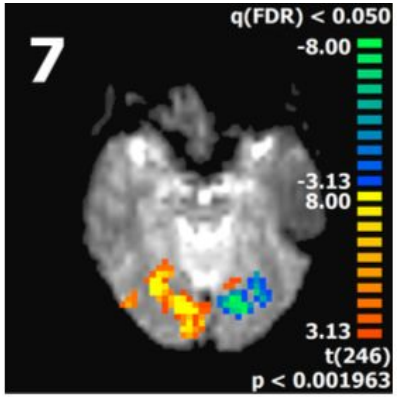


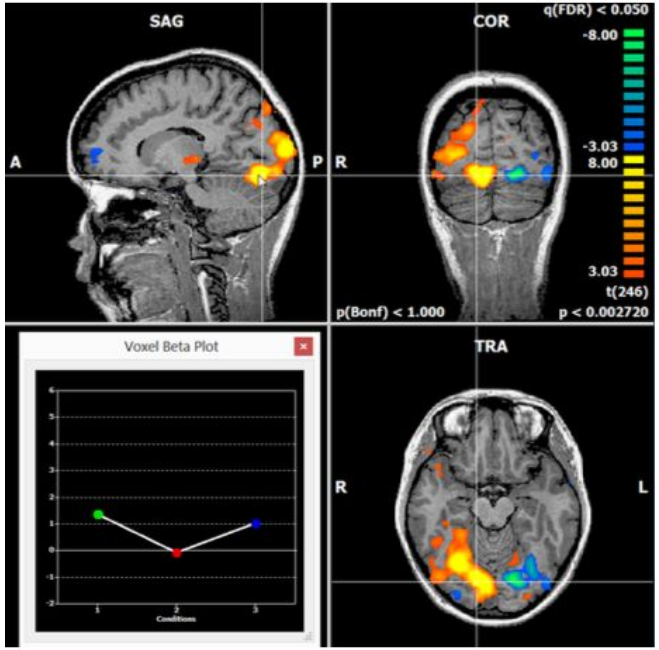
Take home message #6

Se um voluntário estiver a **realizar uma tarefa de forma intermitente** e fizermos **aquisições de sinal ao longo do tempo** podemos construir um modelo que nos informe **quais as áreas que apresentaram maior amplitude de sinal durante a realização da tarefa**.

fMRI statistical map

2D and 3D statistical map based on GLM contrast condition>baseline





Mais, logo nas oficinas RM I e II!