Physics and Brain Imaging

- Nuclear Magnetic Resonance (NMR)
- Magnetic Resonance Imaging (MRI)
- Functional MRI (fMRI)

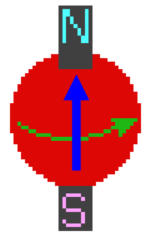
Talk at **Quarknet FSU Summer Workshop,**
July 24, 2017

Per Arne Rikvold

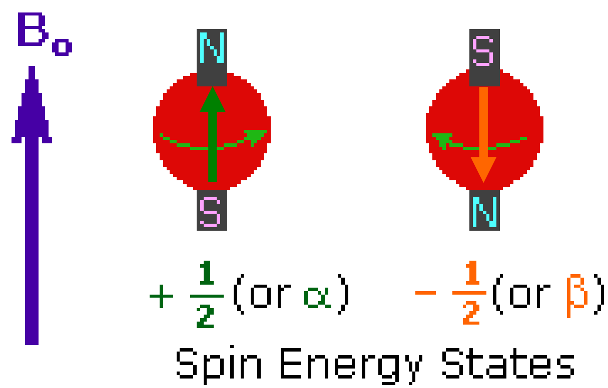
Leonardo da Vinci

Nuclear Magnetic Resonance (NMR)

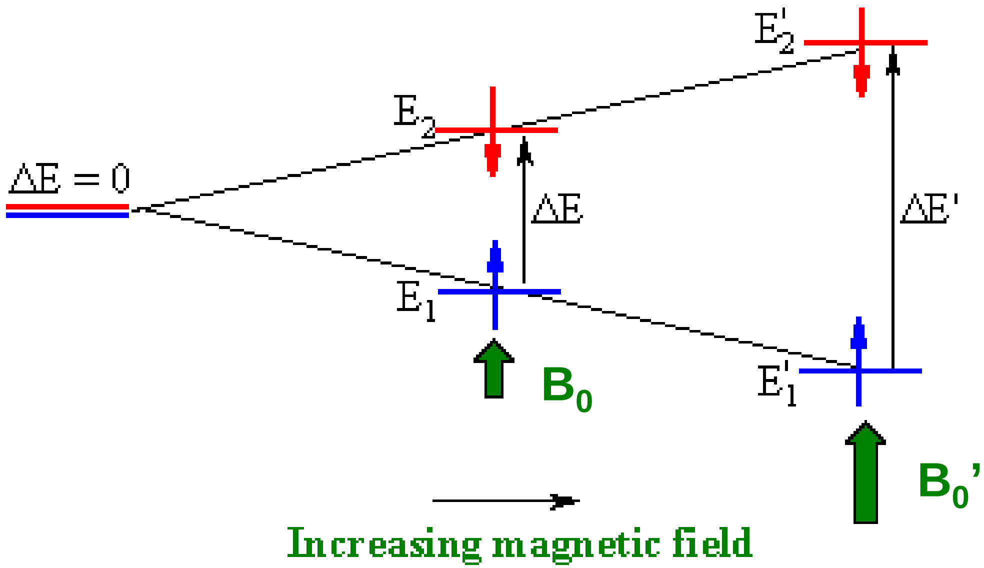
- Protons and neutrons have a **magnetic moment** like little compass needles



- Due to Quantum Mechanics they can only line up **parallel** or **antiparallel** to an applied **magnetic field**

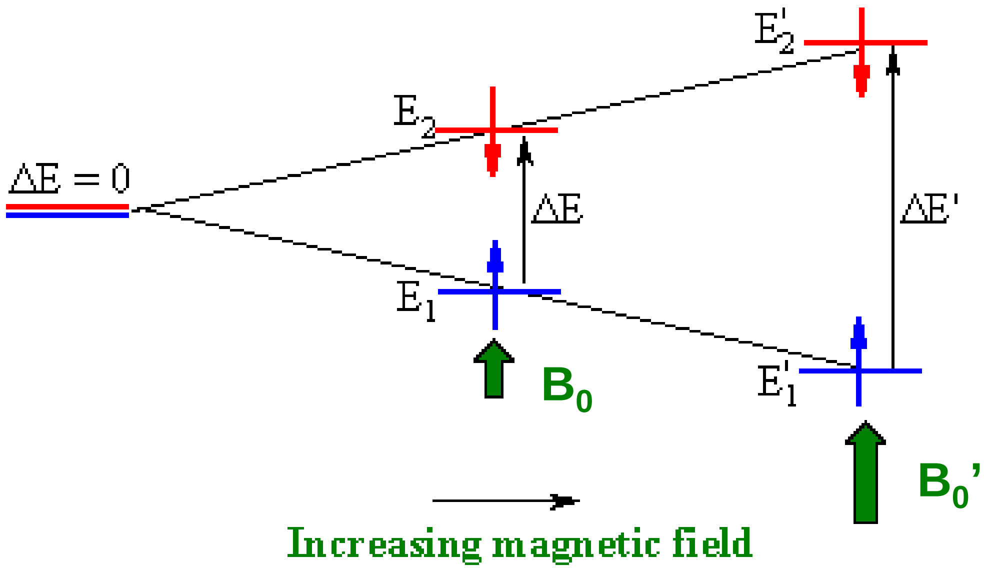


- The two orientations have **different energies**



- The **parallel** direction has the **lowest** energy
- The **antiparallel** direction has the **highest** energy

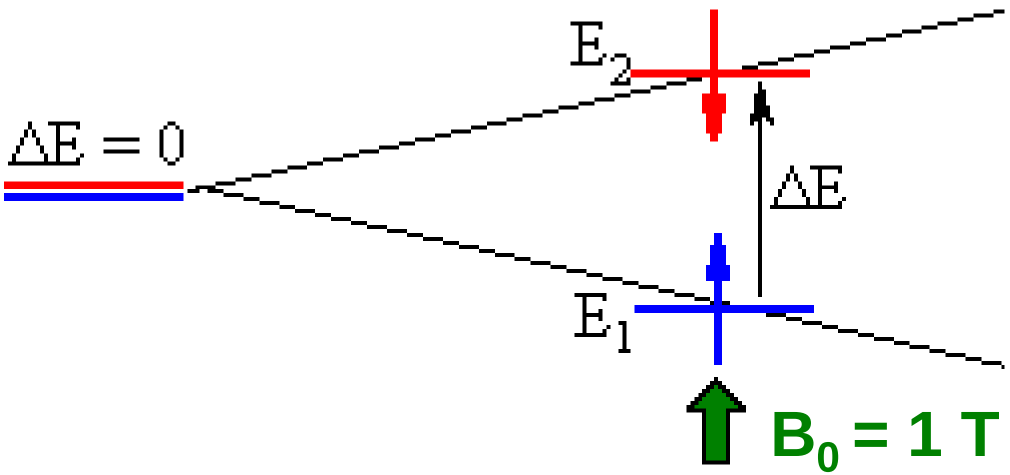
- The energy difference is **proportional to the magnitude of the magnetic field**

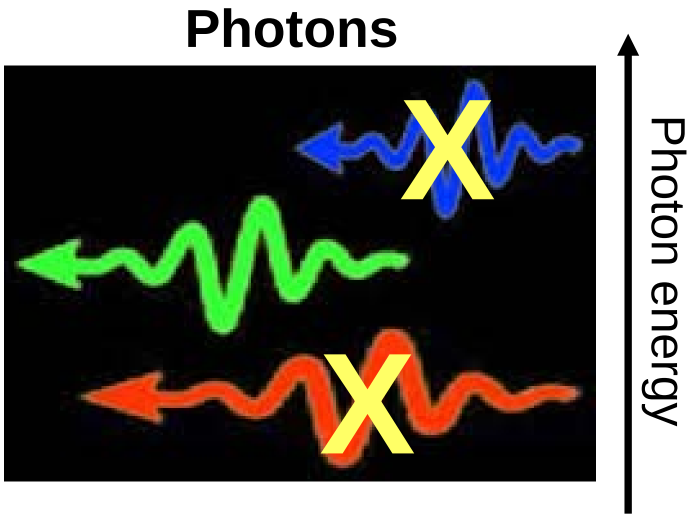


$$\Delta \boldsymbol{E} = \boldsymbol{m}\boldsymbol{B}_{\mathbf{0}}$$

- For a proton (^{1}H nucleus) in a 1Tesla (T) field, $\Delta E = 2.8\text{x}10^{-26}$ J

- We can **excite** the proton from the low-energy orientation to the high-energy orientation by exposing it to a pulse of **electromagnetic radiation of exactly the right frequency (*Resonance*)**



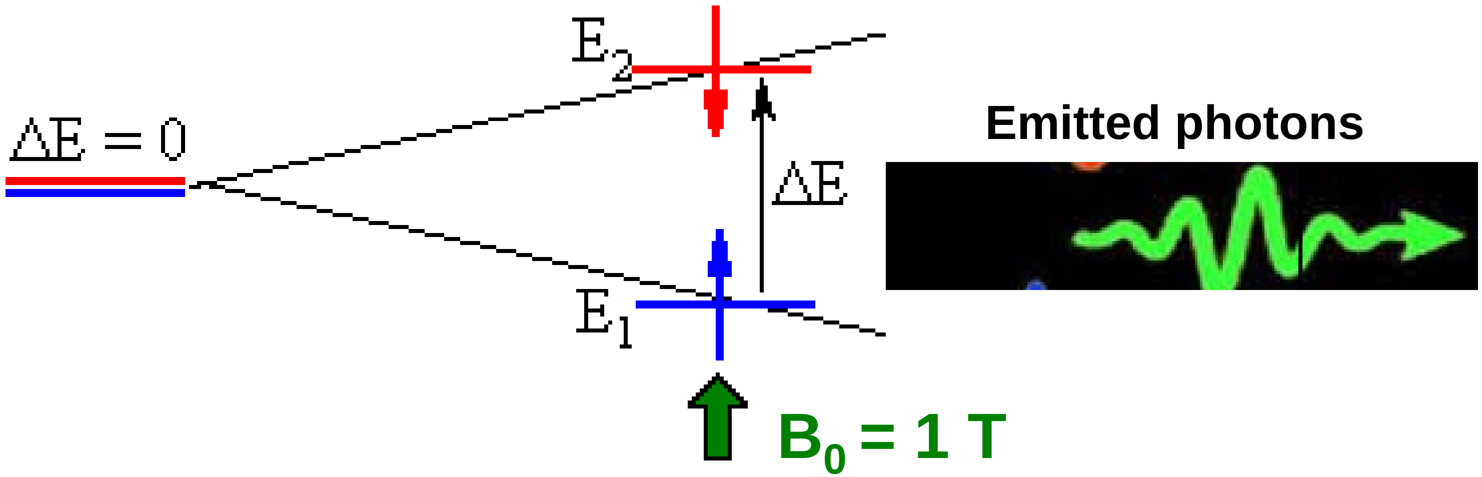


$$f = \frac{\Delta E}{h} = 43\,\text{MHz}$$

Where $h = 6.626\text{x}10^{-34}$ Js is *Plancks Constant*

The FM radio band in the US is 88 – 108 MHz

- Once the exciting pulse is over, the excited nuclei will **decay** randomly to the low-energy state, emitting radiation of ***the same frequency,*** $f = \Delta E/h$



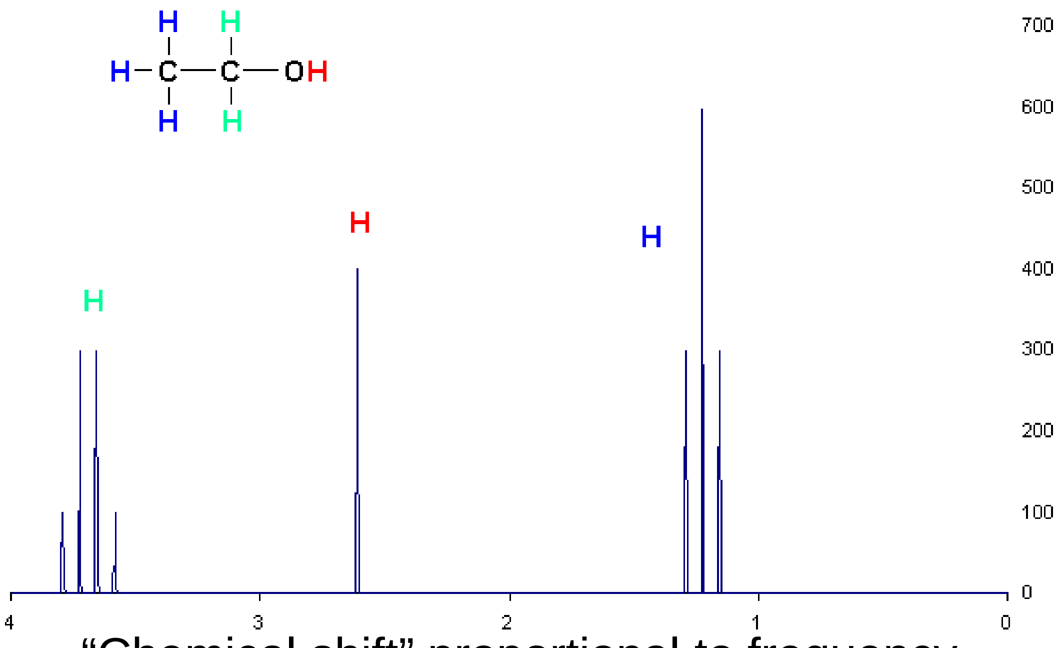
- As the number of exited nuclei goes down, the emitted signal weakens exponentially on a timescale called T_1
- Variations in the local magnetic field also cause signal decay on a timescale called T_2

- Felix Bloch and Edwin Mills Purcell received the 1952 Nobel Prize in Physics for their work on NMR.

NMR Spectroscopy

- In addition to the applied field $\mathbf{B_0}$, the field a particular nucleus "sees" depends on *its environment* through interactions with other atoms in the same molecule, and with other molecules
- This results in *slightly different resonance frequencies*

Example for Ethanol

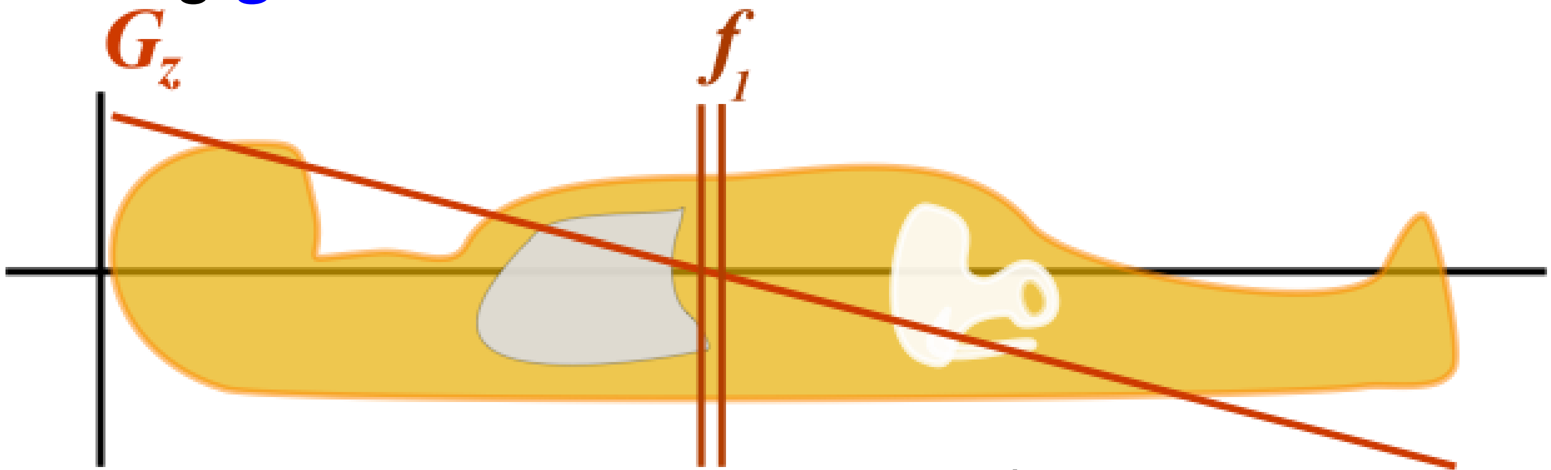


"Chemical shift" proportional to frequency

Magnetic Resonance Imaging (MRI)

- Since tissue is mostly water, Hydrogen NMR is well suited for studying biological specimens.
- BUT:
- The NMR spectra we have discussed so far provide no information about the position in the sample that a particular signal comes from.
- So how can we use NMR for imaging??

- We can vary the magnetic field in space by adding ***gradient fields***.



- With this gradient, a particular ^{1}H resonance frequency corresponds to a particular **slice** along the length of the patient's body.
- With additional gradient fields in the *x* and *y* directions, **specific points in each slice** can be identified.
- With this information we can build a **3D image.**

- The gradient technique was developed in the 1970's by Paul Lauterbur (Stony Brook U., NY) and Peter Mansfield (Nottingham U., UK), who received the 2003 Nobel Prize in Physiology or Medicine for their work.
- The figures show Lauterbur's experiment on imaging two water-filled test tubes. From: P. Lauterbur, Nature **242**, 190 (1973).

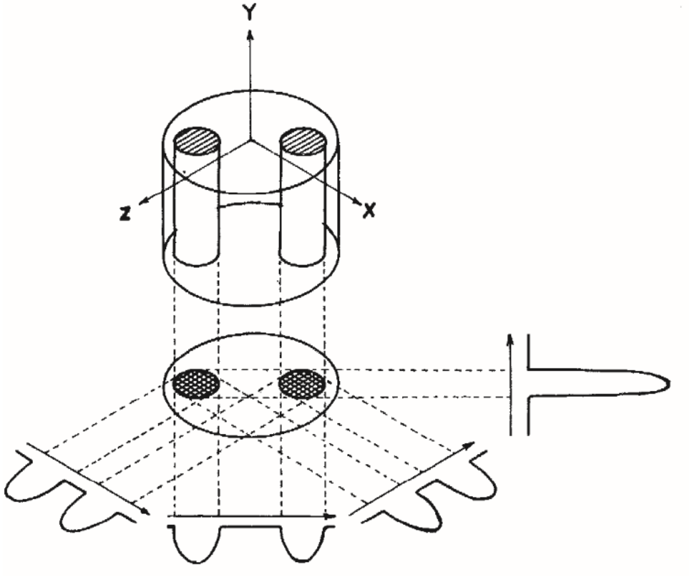
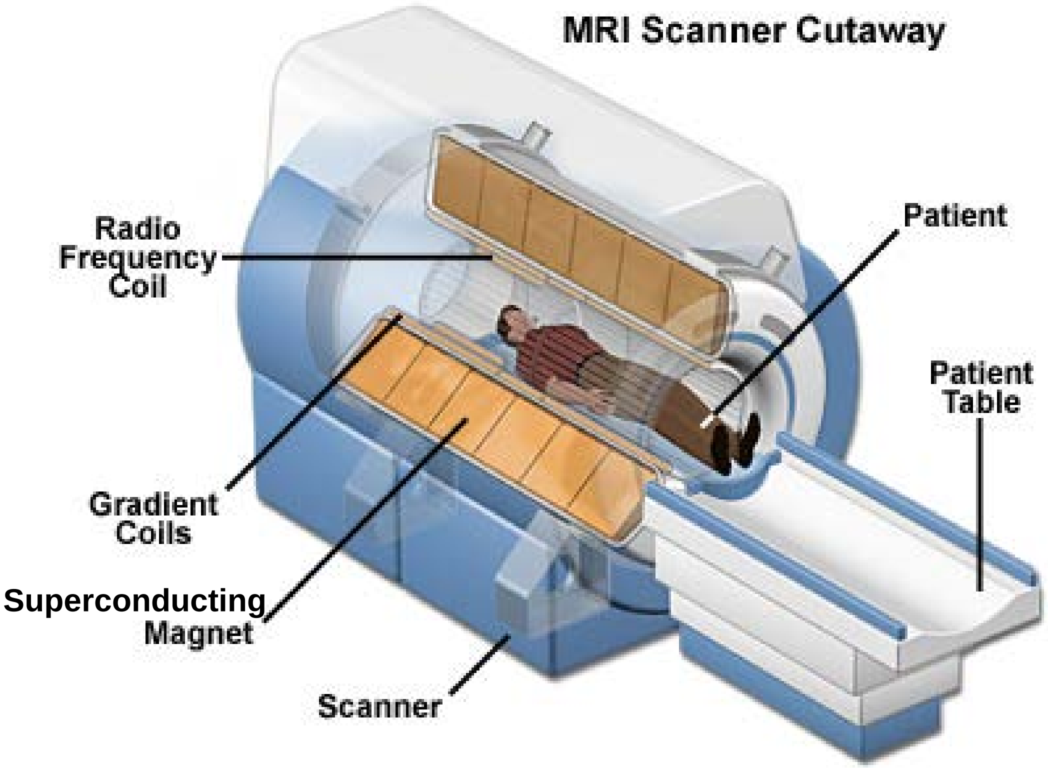
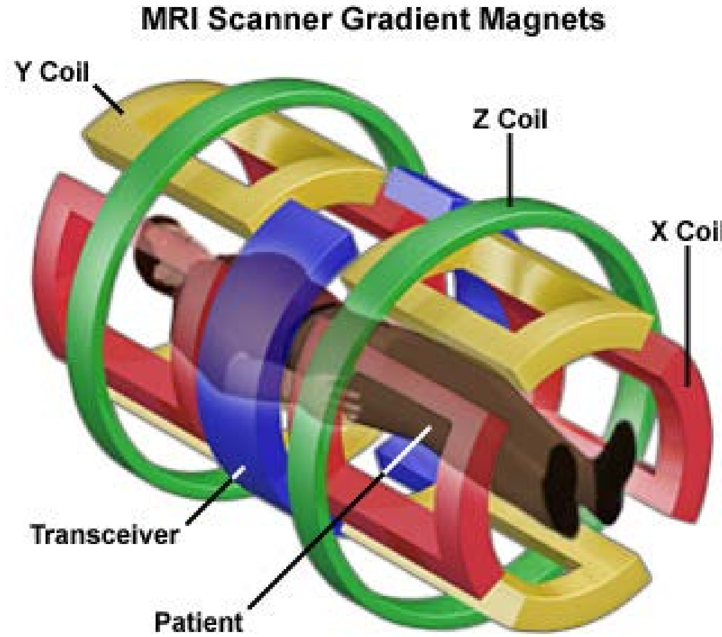


Fig. 1 Relationship between a three-dimensional object, its two-dimensional projection along the Y-axis, and four one-dimensional projections at 45° intervals in the XZ-plane. The arrows indicate the gradient directions.

Fig. 2 Proton nuclear magnetic resonance zeugmatogram of the object described in the text, using four relative orientations of object and gradients as diagrammed in Fig. 1.

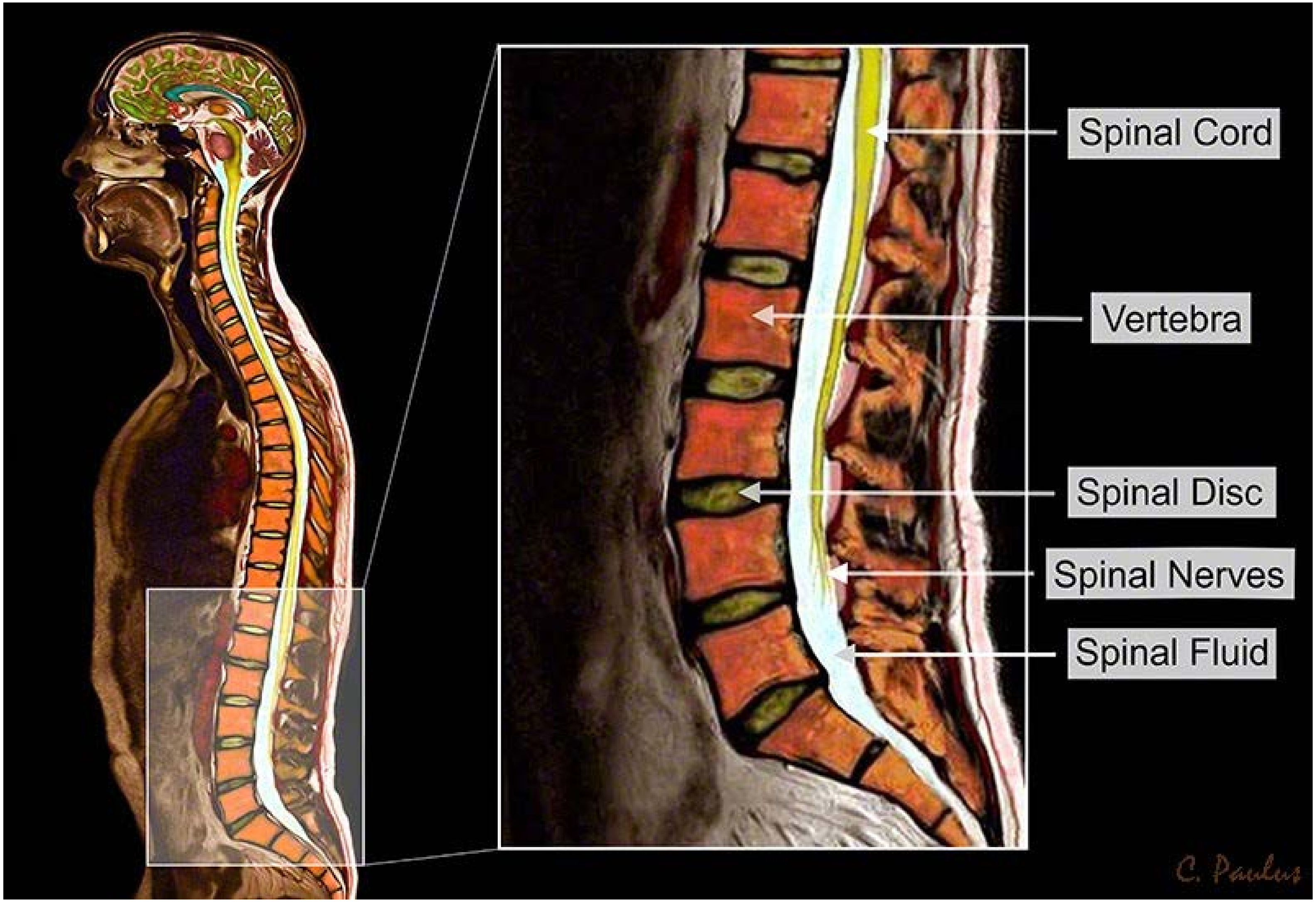




https://nationalmaglab.org/education/magnet-academy/learn-the-basics/stories/mri-a-guided-tour

A medical MRI machine
The typical resolution of medical MRI is around 1 mm

MRI images of various organs

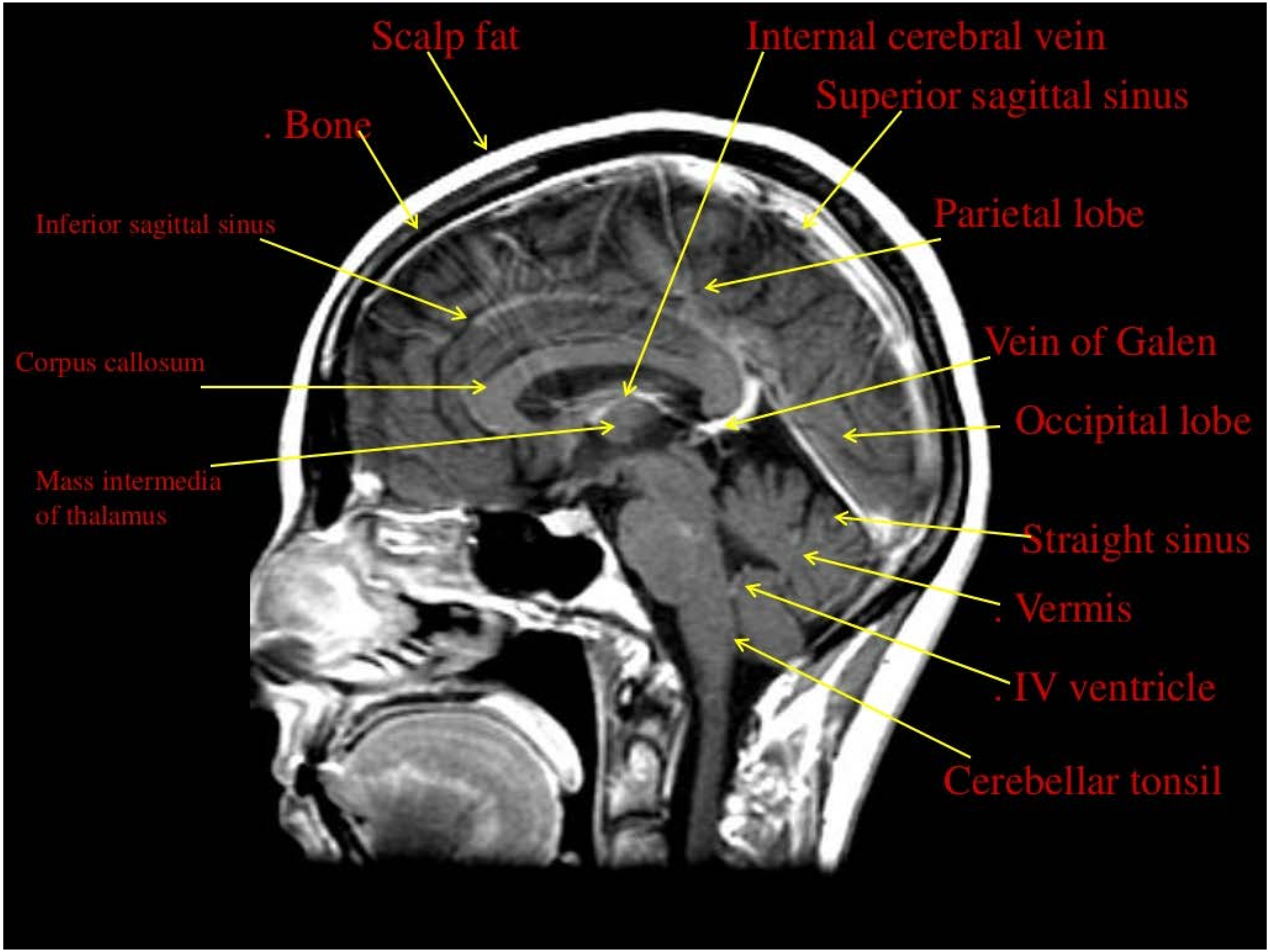


Lower back

MRI images of various organs

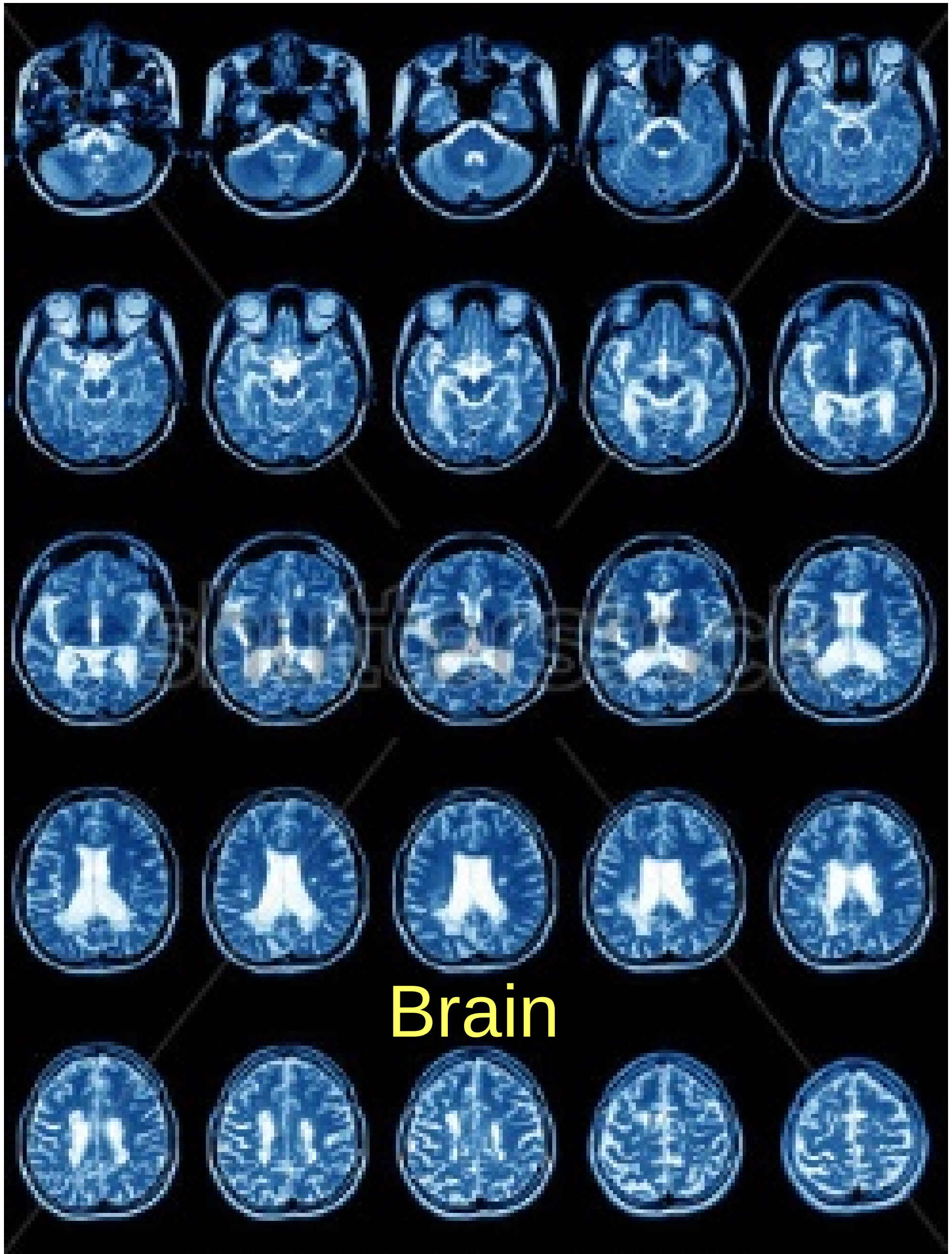
Heart and lungs

MRI images of various organs



Brain

MRI images of various organs

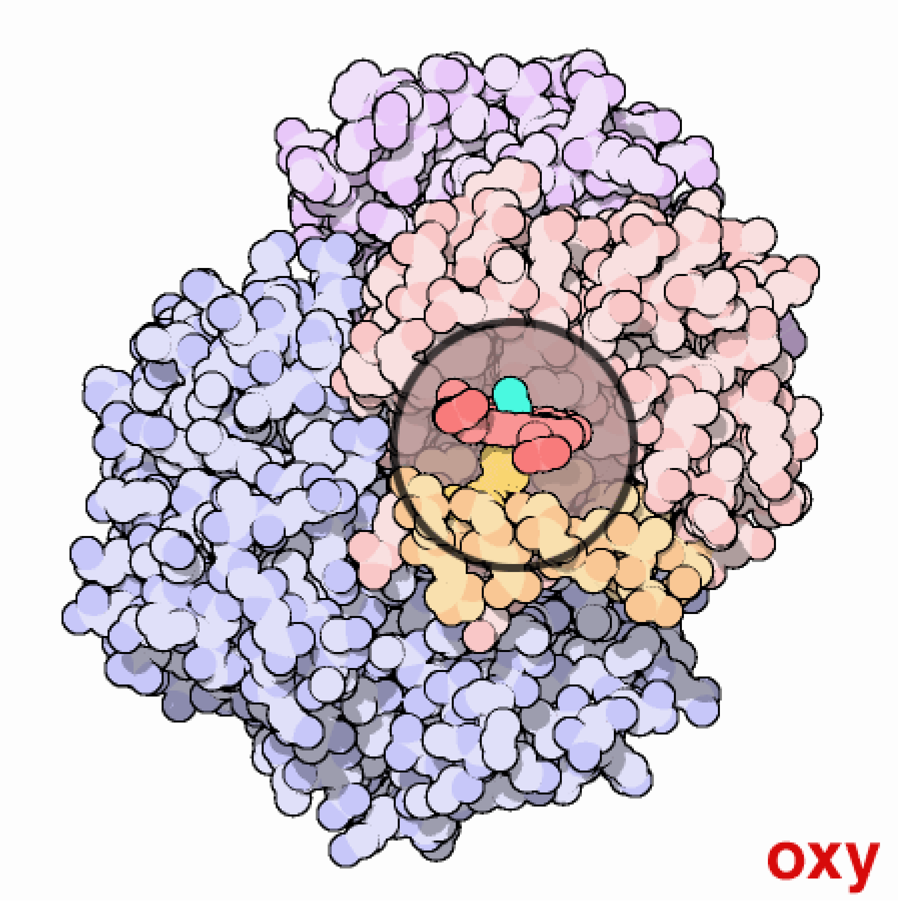


Functional MRI (fMRI)

- Standard MRI can produce high-resolution images of the **structure** of organs.
- **But** a brain MRI says **nothing** about the **activity** of different parts of the brain in response to a particular stimulus.
- **This is the purpose of fMRI.**

The fMRI technique

- Active neurons require more energy than passive ones.
- This requires **increased blood flow** to transport *oxygen* and *glucose* to the active brain region.
- As oxygen is released, **the ratio of oxygenated to deoxygenated hemoglobin in the blood is reduced.**



Oxyhemoglobin has **no magnetic moment** (diamagnetic)
Deoxyhemoglobin **has a magnetic moment** (paramagnetic)

Moving image from http://pdb101.rcsb.org/motm/41

- The different magnetic properties of the two forms of hemoglobin is utilized by the **blood-oxygen-level dependent (BOLD) contrast technique**.
- This technique relies on the fact that the **magnetic deoxy**hemoglobin causes a stronger decay of the NMR signal emitted from the tissue (a shorter T_2 time) than the **nonmagnetic oxy**hemoglobin.
- **So the increased flow of oxygenated blood to the active brain regions causes a *stronger* NMR signal.**

- It takes a couple of seconds for the blood flow to ramp up in active regions.
- So the BOLD method only has a time resolution of a few seconds.
- The spatial resolution is also less than that of ordinary MRI, only on the order of one cm.
- To better locate the active regions, the fMRI image is often superimposed on an ordinary MRI image.

FSU’s new fMRI machine

fMRI images

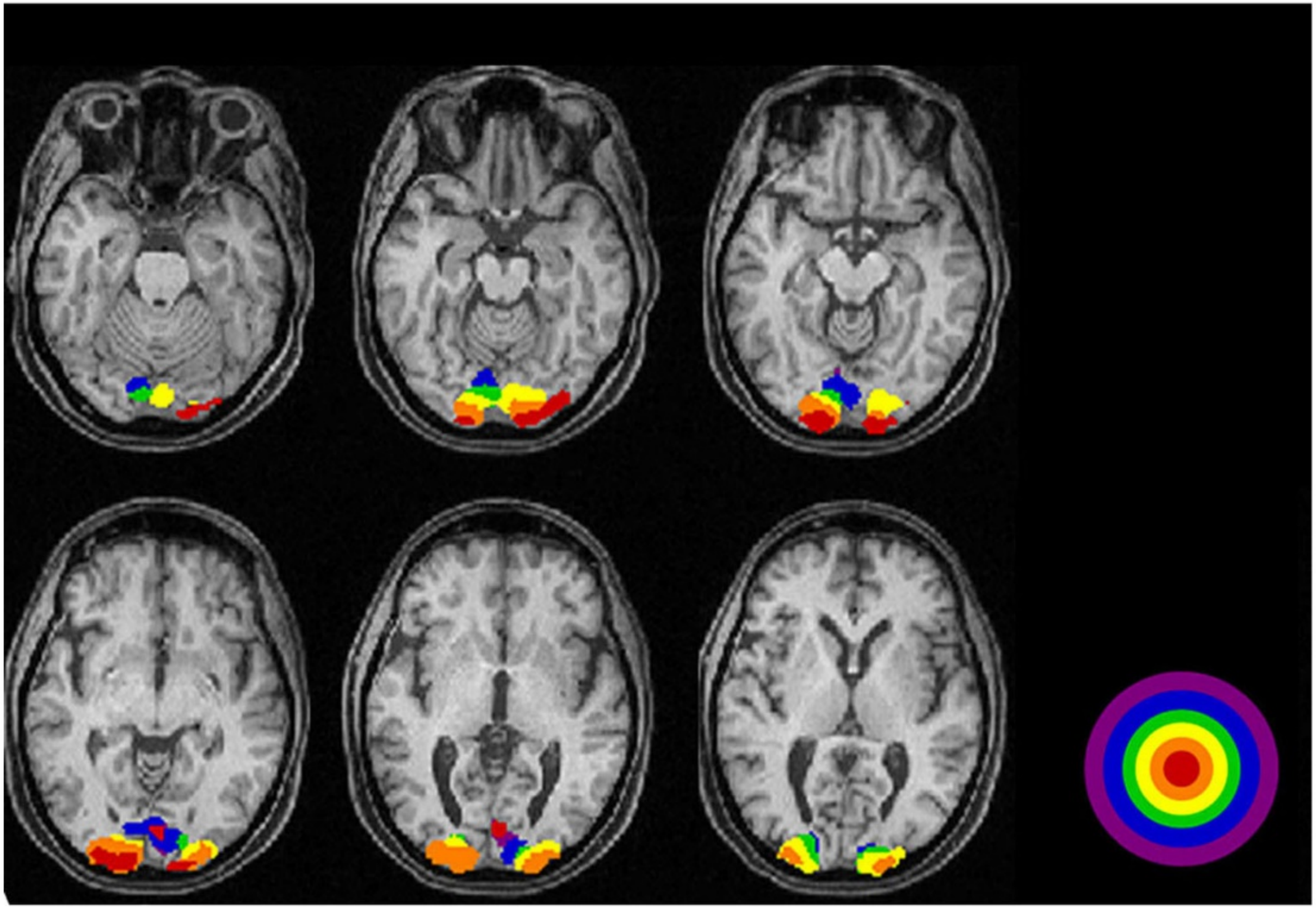
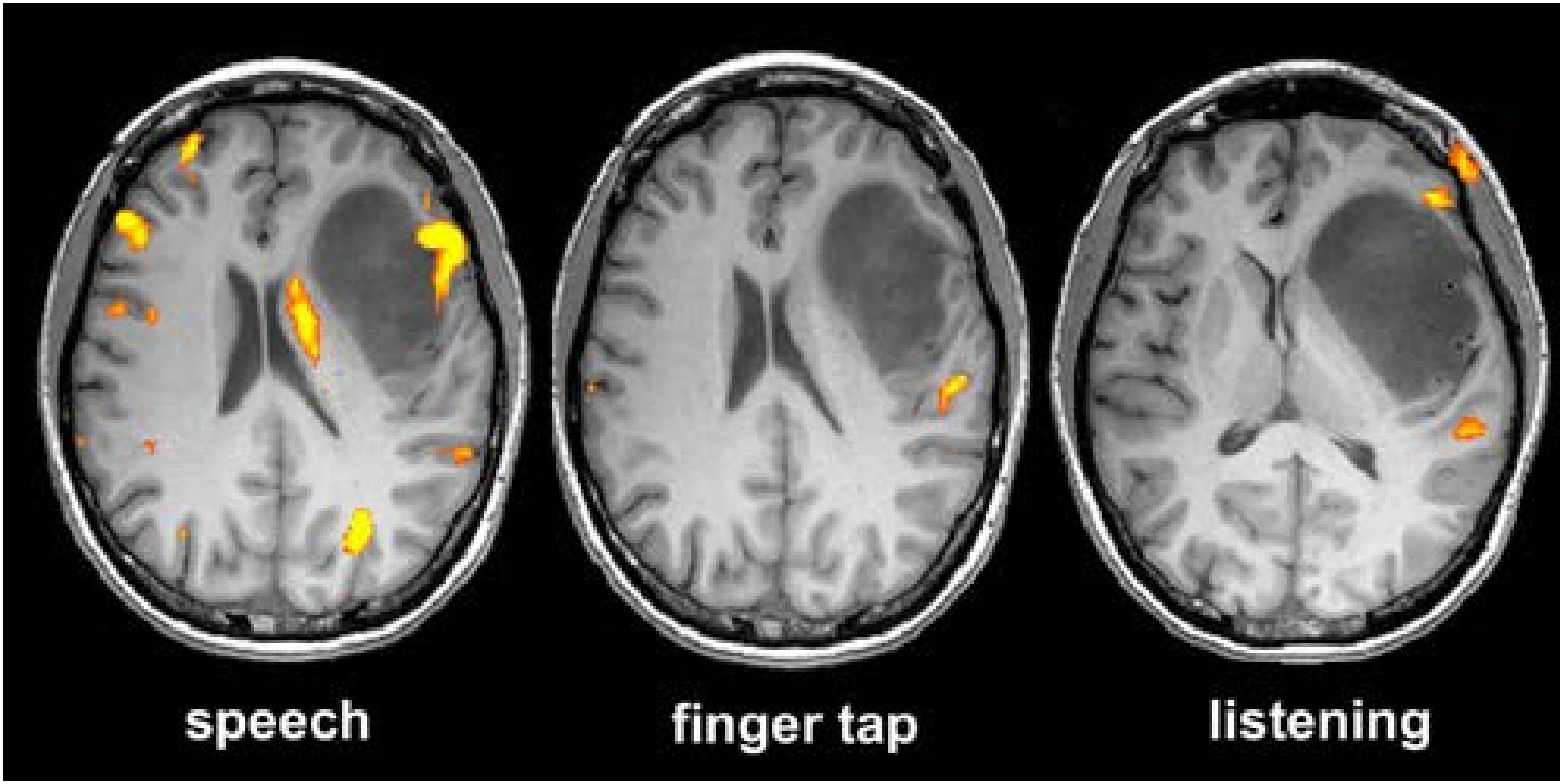
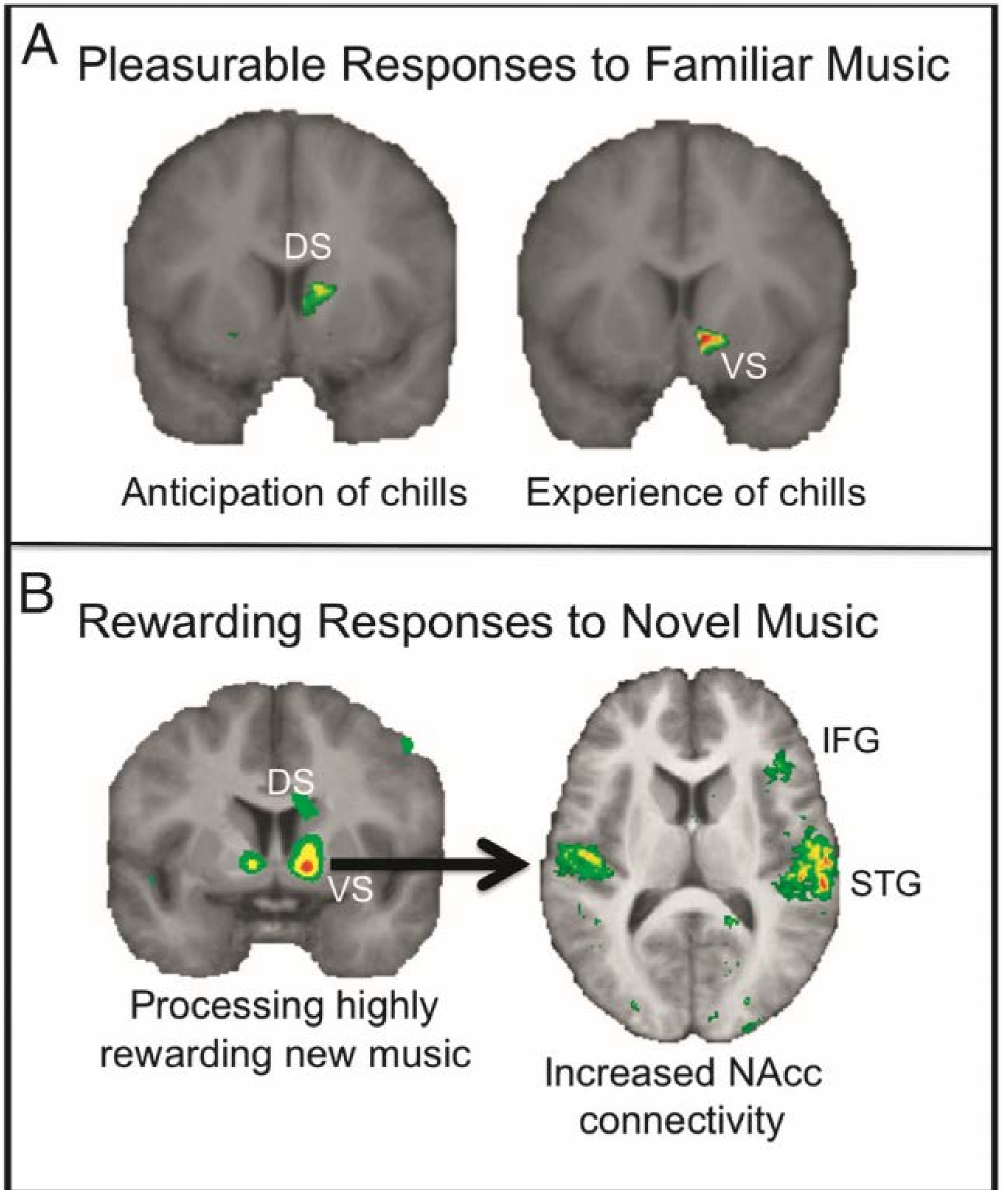


Fig. 3. Functional MRI sections of the occipital visual areas showing maximal blood flow (activity) during visual pattern stimulation. Maximum is red, minimum is blue to purple.

Visual stimulation


speech
finger tap
listening



From: R.J. ZATORRE, V.N. SALIMPOOR, From Perception to Pleasure: Music and Its Neural Substrates. In: In the Light of Evolution: Volume VII: The Human Mental Machinery, Ch. 13. National Academies Press, 2014.

THANK YOU!