Single-Atom Nuclear Magnetic Resonance Model

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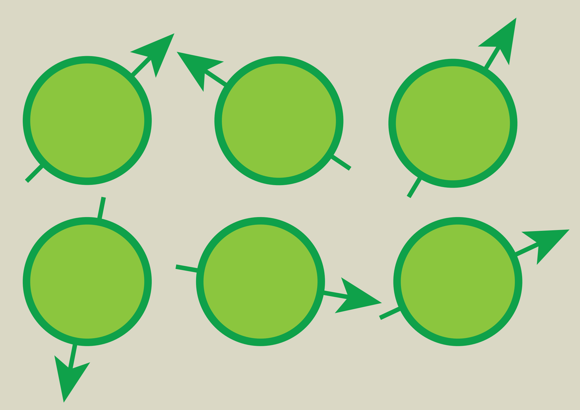
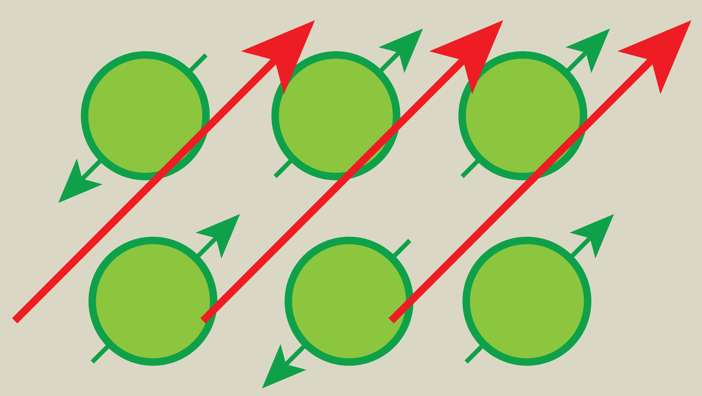
How NMR works*

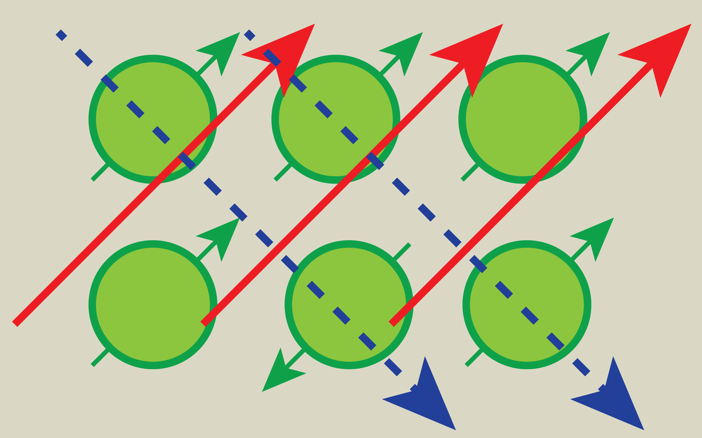
Atomic Nuclei have a magnetic moment related to their quantum mechanical spin. Normally these magnetic moments are aligned randomly.

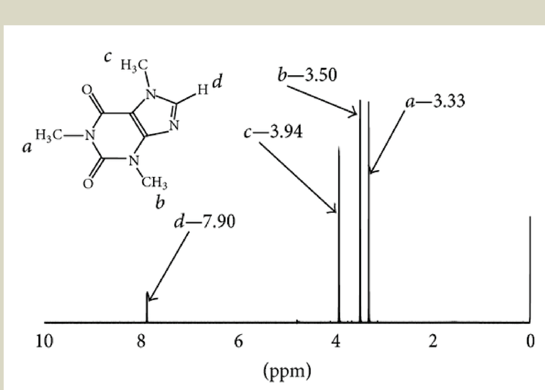


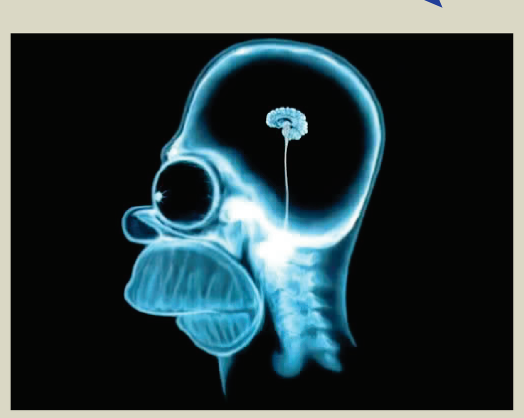
When an external magnetic field is applied, the magnetic moments align either parallel or anti-parallel to the field. These two alignments have a different energy.



By applying an electromagnetic wave at the right frequency we can 'flip' the spins between the two alignments. This produces a signal that we can then use for spectroscopy or medical imaging of the sample.







*Simplified version that glosses over a lot of interesting physics and chemistry.

NMR is best known as Magnetic Resonance Imaging (MRI) used for medical imaging. (They call it MRI rather than NMR because the word "nuclear" makes people nervous.)

It's also used in Chemistry and Physics for high-resolution spectroscopy, to determine molecular structure, isotope percentages, and so on.

This is ***NOT*** what we're doing. We're making a macroscopic model of a single nucleus in NMR, to help students understand how NMR works.

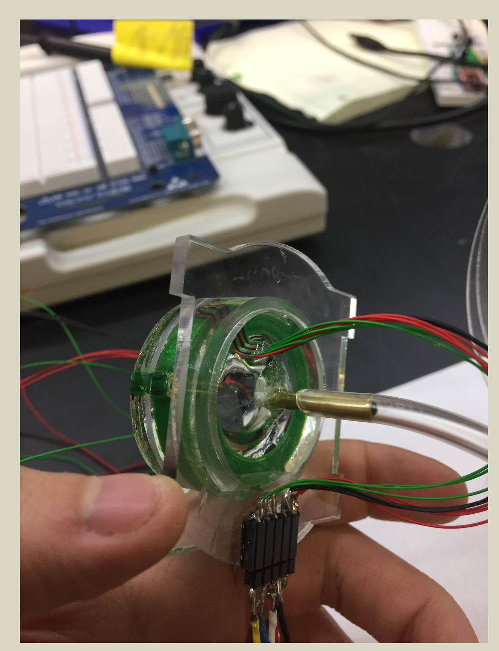
Our design

For our 'atomic nucleus' we're using a one-inch diameter acrylic sphere with a magnet at the center. This has a magnetic moment (like a nucleus) and a spin (kind of like the nucleus) but unlike a nucleus we can actually see it and watch the spin flip at the resonant frequency.

The magnetic field and the electromagnetic wave we can provide by using crossed Helmholtz coils. This sounds fancy, but they're just coils of wire on a frame that holds them in just the right place. We don't need the super-strong magnetic fields of a commercial NMR spectrometer or MRI machine, because the necessary field strength scales down as the size of the model scales up.

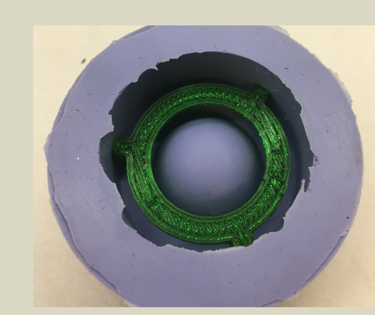
What we *do* need is a way of holding the atom in place that allows it to spin freely in any direction, and for that we chose to use an air-bearing. This is a spherical socket, barely larger than the sphere, with an air-jet at the bottom so that the sphere is supported on a nearly-frictionless cushion of air. (Kind of like a really boring air-hockey table.) We want to be able to make quantitative measurements of the behavior of the sphere, so we decided to embed magnetic field sensors in the socket to track the alignment of the magnet in the sphere.

One of the many challenges with this project is that the sensors have to be exactly aligned or they give erroneous results. After trying a number of different alignment jigs, we finally settled on a design where we glued the sensors to a 3D-printed alignment frame, put the frame in the mold, and then cast the socket with the frame and sensors inside. This works!

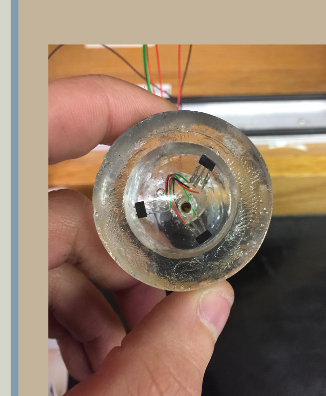


On the left is the final design, fixed to the mounting plate for assembly in the NMR apparatus. For the air-jet supply, we just used a fish-tank pump.

On the right is a picture of the socket mold, with a sensor frame (no sensors attached) in place as if ready for casting.



Of course we found a lot of things that don't work... For example, if you use the acrylic sphere as part of the mold, and you're casting with polyester resin, there is no mold release compound in the world that will allow you to separate the sphere from the socket when you're done! Epoxy casting resin is easy to use and releases the acrylic sphere, but it shrinks. Eventually Jaydie Lee* managed to make us a working mold using a three-step process involving clay, casting resin, and silicone molding compound. This flexible silicone mold allows us to cast the final socket in clear polyester, which has sufficient dimensional stability for what we need and also allows visual inspection of the internal sensors and wiring.

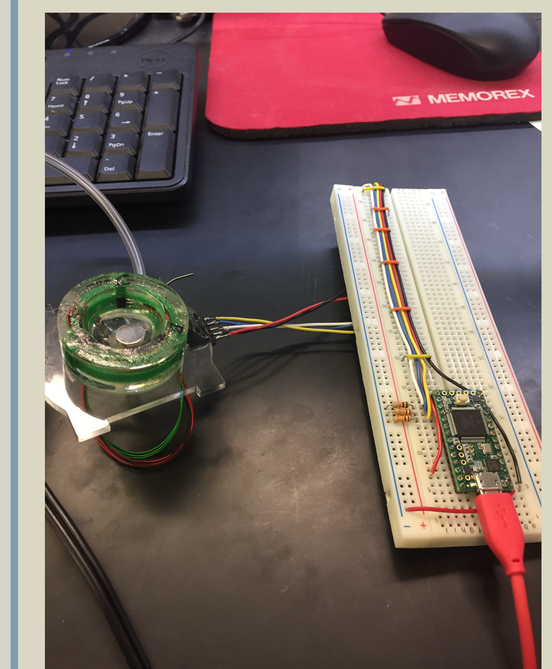


This early try almost worked, but the sensors are slightly mis-aligned. Start over, this time with a sensor frame!

*Jaydie Lee's work made this project possible. Without his efforts, we'd have probably given up on casting!

Next Steps

We've successfully demonstrated (and can repeatably make) a working air-bearing with embedded magnetic sensors. Using a microcontroller (Teensy 3.2) as a bridge between the sensors and a computer, we're able to track the alignment of the sphere in real time.



That's the core of the device. Now we're building the frame that holds the Helmholtz coils with the spinning sphere in the center. This portion of the work is progressing more smoothly.

We have designed a frame that can be laser-cut from 3mm acrylic plates. The pieces are then stacked and bolted together to form the coils. A system of tabs and notches in the pieces holds the coils in the exact alignment necessary.

The final assembly will have a Programmable System on Chip (PSoC) -based control board to drive the coils and communicate with a computer for data collection.