**Questions to answer by end of project:**

1. What is the area of E&M that you are doing research on?
    a. The Zeeman Effect.
2. What are the questions that you are trying to answer about this area?
    a. How does the universe work.
3. What theoretical models can be used to answer those questions?
    a. Perturbation theory.
4. What analytical and computational work did you do to answer those questions?
5. What were the resulting predictions that your work produced?
6. What are the limitations of what you have done? * What are some remaining open questions?
7. What did each member of your pair contribute?

**Questions for this week:**

- Who are the partners in this team?
    - Antonius Torode and Eric Aboud
- What are you and your partner proposing to do?
    - Model the effect of a uniform magnetic field on an atom (The Zeeman Effect)
    - Model the corrections that the Magnetic field has on the Hamiltonian and use perturbation field to solve for energy and wave function corrections that arise from the field.
    - Discuss these changes and how they affect real world applications using the example of MRI technology.
- What area of E&M will you be conducting original calculations for?
    - We can determine the splitting for various atoms and determine if various atoms provide a change to MRI resolution/imaging ability.
    - We can build the hyperfine structures for various atoms/molecules and compare them. We can determine how the splittings change with different magnetic field magnitudes.
    - We can also discuss how fluctuating magnetic fields will induce electric fields (Stark effect). We may go into some detail about hyperfine corrections due to the Stark effect.
    - We could also talk about adding a radio frequency source to the atoms and describe the x-ray emission (using poynting vectors and describing the EM wave) for a hydrogen atom.
- What source material are you drawing from?
    - "Hydrogen atom in a strong magnetic field" - http://www.sciencedirect.com/science/article/pii/0022369756900208
    - "The Zeeman Effect in Oxygen" - http://link.aps.org/doi/10.1103/PhysRev.80.396
    - "Zeeman Effect and Hyperfine Splitting of Positronium" - http://link.aps.org/doi/10.1103/PhysRev.85.1047
    - "Theory of Zeeman Effect in the Ground Multiplets of Rare-Earth Atoms" - http://link.aps.org/doi/10.1103/PhysRev.122.1802
    - Intro to Quantum Mechanics - David J. Griffiths

- Intro to Nuclear Physics - Kenneth S. Krane, P.616-650
- What has been done so far and what are you going to do? It's ok if it's a solved problem, but you will need to reproduce what has been done and extend it beyond what your reference material offers.
  - Hyperfine structures have been built for many atoms and molecules. With references, we can replicate/complete the calculations for the hyperfine splitting due to the Zeeman effect for particular atoms. We can go beyond the reference material and compare the splittings and how the magnetic field dependence changes them.
  - We may continue to describe how the hyperfine splittings for various atoms can serve practical purposes, such as how they may affect modern MRI techniques.
  - Perturbation Theory is a useful way of determining higher order corrections to the wave function and energy solutions in Quantum mechanics. These calculations can be simple such as in the Hydrogen atom, or much more complex. We can perhaps demonstrate this.

**Some useful Information and sources:**

- The Zeeman Effect - "When an atom is placed in a uniform external magnetic field B, the energy levels are shifted. This phenomenon is known as the Zeeman Effect" - Griffiths
- "The splitting of the lines in a spectrum when the source of the spectrum is exposed to a magnetic field. It was discovered in 1896 by Pieter Zeeman (1865–1943). In the **normal Zeeman effect** a single line is split into three if the field is perpendicular to the light path or two lines if the field is parallel to the light path. This effect can be explained by classical electrodynamics in terms of the speeding up and slowing down of orbital electrons in the source as a result of the applied field. It has also been explained in terms of the Bohr theory and quantum mechanics. The **anomalous Zeeman effect** is a complicated splitting of the lines into several closely spaced lines, so called because it does not agree with classical predictions. This effect is explained by quantum mechanics in terms of electron spin. See also Paschen–Back effect." - Rennie, Richard. "A Dictionary of Chemistry (7 ed.)." Oxford University Press. ISBN-13: 9780198722823. 2016.
- http://www.nobelprize.org/nobel_prizes/physics/laureates/1902/zeeman-lecture.html Nobel lecture by Pieter Zeeman after receiving the Nobel Prize for physics, 1902"
- Zeeman Effect in MRI - "The 1H nucleus consists of a single proton. Its spin angular momentum (and its magnetic moment), like that of the electron, can take on only two values when placed in a magnetic field: we call these 'spin up' (parallel to the field) and 'spin down' (anti-parallel to the field), as suggested in Figure 1. When a magnetic field is present, the energy of the nucleus splits into two levels as shown in Figure 2, with the spin up (parallel to the field) having the lower energy. This is like the Zeeman effect for atomic energy levels. The difference in energy ∆E between these two levels is proportional to the total magnetic field BT at the nucleus: ∆E = k · BT The proportionality constant k in this expression is different for different nuclides." http://www.fisme.science.uu.nl/pos/MI_2_3_4%20stfs%20mri.pdf
- How MRI works - https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1121941/

**Week 2**

For the project we plan to calculate the hyperfine structure (zeeman effect) for Hydrogen and another atom. Since these calculations become exponentially more involved with the difficulty of the atomic nuclei structure, we will perhaps try to look at simple atoms such as deuterium. We will then find how different magnetic fields affect the structure and determine if any anomalies occur for different magnetic fields. It will be up to both of us together to complete these calculation (since they are involved).

The largest part of the project will be creating methods of calculating the hamiltonian. This will probably take the most time, which we could hopefully expect to have completed in a couple weeks (since <Eric> may be gone multiple times to visit grad schools). Once that is complete we should take another week to compute the effect that different magnetic fields have on the structure. We will numerically or graphically represent the results for a range of cases with different magnetic field strengths. We will start with the simple hydrogen atom calculations and determine the correction terms due to a magnetic field. From this, we can determine the hamiltonian and use perturbation theory to solve for energy and wave function corrections. This may prove different for higher energy states of Hydrogen due to degeneracies which is where a computer system will be applied to help solve for the corrections. We may only be able to achieve results for a couple low level n states but we will see.

If we have time at the end, we can look at how a linearly changing magnetic field can induce an electric field. Since a time dependent magnetic field will cause an induced changing electric field, this will cause the stark effect to play a role in the corrections to the Hamiltonian. This would be very complicated on it’s own so we can perhaps look at a specific case for the hydrogen atom, such as the ground state and choose a simple magnetic field changing in time to explore how this affects the perturbations. This is where we can involve much more E&M into our project, but I suspect it will be far too much work to try and generalize the effects of a changing magnetic field any.