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Teaching about the Physics of Medical Imaging

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Abstract. Even before the discovery of X-rays, attempts at non-invasive medical imaging required an understanding of fundamental principles of physics. Students frequently do not see these connections because they are not taught in beginning physics courses. To help students understand that physics and medical imaging are closely connected, we have developed a series of active learning units. For each unit we begin by studying how students transfer their knowledge from traditional physics classes and everyday experiences to medical applications. Then, we build instructional materials to take advantage of the students' ability to use their existing learning and knowledge resources. Each of the learning units involves a combination of hands-on activities, which present analogies, and interactive computer simulations. Our learning units introduce students to the contemporary imaging techniques of CT scans, magnetic resonance imaging (MRI), positron emission tomography (PET), and wavefront aberrometry. The project's web site is http://web.phys.ksu.edu/mmmm/.

Keywords: Teaching, physics, medical, imaging, CT scans, MRI, optics, eye

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INTRODUCTION

Modern Miracle Medical Machines is an educational research and development effort to teach some physics in a medical context. Because students who wish to become either physicians or veterinarians will complete one physics course, this context should be important and interesting to them. In this project we are focusing primarily on medical imaging. The materials are for the algebra-based university level. We are not trying to create an entire new course. We have tried to create relatively short materials that could be put into an existing course. This approach enables faculty to change part of a course which is much easier than changing all of it at once.

MEDICAL EDUCATION IN THE UNITED STATES

The university education for medical students in the United States is somewhat different from many other parts of the world. First, both human and veterinary medicine is a study that students do after they have completed a Bachelor's degree. They go to the university and complete a Bachelor's degree, frequently in a science but not always. Then, they attempt to be admitted to a medical college. The level of competition for admission to medical colleges is very high. Thus, these students are frequently very interested in doing well in the sense of getting high marks in their classes but not necessarily doing so well

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that they really learn something. The phrase frequently used for this is "pre-meds" – pre-medical students. They are very competitive for grades and are usually very bright students. However, grades tend to be more important than learning so that is one of the reasons we want to present physics in a way that will motivate their learning.

Typically, the physics course prior to the medical studies is algebra-based although in some institutions it is now calculus-based. In addition these students will complete several biology courses, two or three courses in chemistry, and a variety of other general courses at the university.

The pre-med physics course at most universities in the United States is a rather standard introductory course in physics. Some but not all faculty have adopted some type of interactive learning. Thus, typically the course will contain some lectures, some practical work, and some problem-solving sessions. Usually the course is primarily physics with perhaps a few examples from medicine. The focus is mostly on quantitative problem solving. As other papers at the conference have discussed quantitative problem solving does not necessarily lead to understanding in physics in general.

OUR APPROACH TO RESEARCH AND DEVELOPMENT

Our goal is creating learning materials that are motivational for the students. Our approach is to conduct some research on students' reasoning and their mental models as they are trying to apply some physics that they have already learned to some issues in contemporary medicine. Based on the results of this research we developed some active engagement instructional materials that connect the physics to medical diagnosis and medical procedures - in our case primarily diagnosis. Then we try to integrate these materials into the course throughout the whole year.

Our approach is to focus on the physics and not the medicine. We are not trying to teach a future physician how to interpret a magnetic resonance image that they might get from a patient. We do not know how to do that, but we do understand the basic physics that is underlying the medical imaging procedure. We are hoping that we can help the students understand that physics better. We focus primarily on qualitative issues rather than quantitative issues so that we can teach some conceptual understanding. To accomplish this, we use analogies and visualizations rather frequently.

We have developed materials for the following medical applications.

History of Medical Imaging
Eye Diagnosis, Corrections & Surgery
Magnetic Resonance Imaging (MRI)
Positron Emission Tomography (PET)
X-rays & CT Scans

In this paper we will concentrate on eye diagnosis, MRI, and PET.

In all of our development efforts, we do the research first, then develop a lesson, and finally use that lesson in research again. Thus, this process is similar to the approach presented by McDermott in this volume. The research first gives us a basis for developing the lesson and then we try to validate that lesson by using it with students in a variety of different situations and measuring its effectiveness. Of course, we almost always need to make some changes and go back through this cycle more than one time.

Our Two-Step Research Process

The research is a two-step process. We start by trying to understand what the students already know. Then, we investigate how they apply some of this information if they are challenged with applying it to an application that they do not normally see, in this case a medical application. We usually conduct this investigation with a clinical interview. This interview is partially structured in that it contains some questions that we will ask the students. However, it is not totally structured because some of the students' answers might be quite interesting and/or unexpected. In those cases we need to ask side questions to understand better the students' responses. Once we have analyzed these responses and have developed the first draft of the lesson, we conduct a teaching/learning interview. In these interviews we work with small groups of students who are learning while they are applying physics to a medical context. We analyze what they are understanding and how they are understanding it, as well as what we need to add to make them understand the concepts better. This approach is different from interviewing to see what a student knows. Instead, we are investigating the process that the students go through as they are attempting to learn something new. We also look at how they interact with each other as they are learning because we can learn a lot about their thinking as they help each other learn.

An important aspect of the teaching-learning interview is the concept of the Zone of Proximal Development. This idea is a rather long saying that students learn best if you take them in small steps from what they already know to what you want them to know. If we make the steps too big, they will have difficulty in the learning process.

AN EXAMPLE LESSON: WAVEFRONT ABBEROMETRY

This first example was primarily the work of Dyan McBride, a former graduate student. The idea is that the way that one does diagnosis of eye defects is not the simple process of reading the traditional eye charts with different lenses then determining which lens is better. That process is still performed but it is being replaced by more sophisticated techniques. Particularly if a physician is planning on using Lasik surgery to modify your eyes, you want him or her to know very, very well what's wrong with your eyes. Because once they have made the changes, they cannot go backwards and put your eye back the way it was before. So, wavefront aberrometry is the new process to diagnose vision defects.

The basic idea is that a low powered laser is directed into your eye and focused on the retina. That spot on the retina becomes, in effect, a secondary source of light and the light comes back out into a detector. In a simple model of this process if your eye is perfect the laser scan across various parts of it will produce a nice evenly spaced grid. If there is something wrong, then the result will not quite be a grid. (See Figure 1) Through a fairly sophisticated process, actually sophisticated mathematics using Zernike polynomials, the eye doctor's computer can provide much information about what is wrong with the eye. That information can then be put back into another computer which drives the laser in Lasik surgery. Or in those of us who do not like lasers messing with our eyes, the information can be used to drive a lens making apparatus.

FIGURE 1. The grid on the left is a simulation of the grid from an eye with no defects, while the one on the right represents significant vision defects. (Courtesy of Prof. Hartmut Wiesner, Ludwig-Maximilian University, Munich).

While the detailed analysis is a fairly sophisticated process, the basic physics underlying it is somewhat straightforward. So we have tried to build a lesson using hands-on models and computer simulations so that students can understand the underlying physics. We have used several different eye models for this; the most sophisticated of which is shown in Figure 2.

Several other models are available. Pasco, for example, sells a nice one that is based on a very old version. The one nice feature about the model in Figure 2 is that it's quite similar to the 3-D water lens that was on display at the conference. The lens for the eye in this model is two pieces of transparent plastic which are sealed together and filled with water. As more water is added to it or removed from it, the lens gets thicker and thinner. As a result the focal point of the lens changes. This process mimics what happens in our own eyes when our eyes accommodate for looking at different distances. And it works quite well for us and for the model.

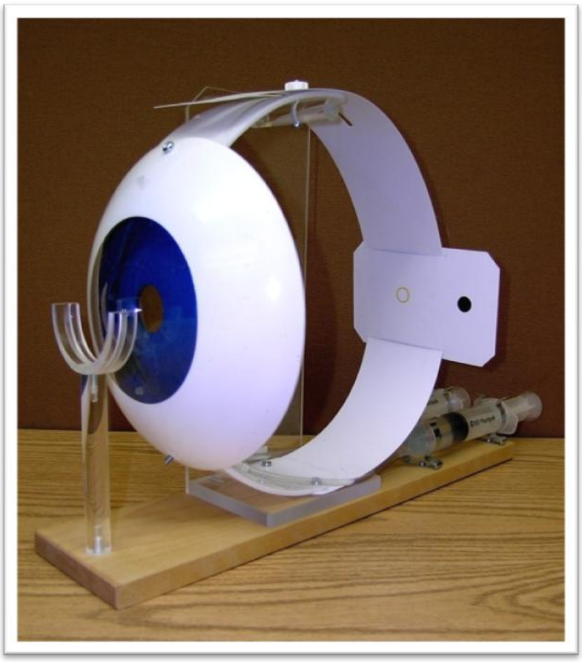

FIGURE 2. A functional model of the optical system of the human eye. Available from several sources such as http://www.universalmedicalinc.com/)

For our purposes we put a small light source at the back and move it around. Then we can obtain for a normal lens a nice even grid similar to the one on the left side of Figure 1. If on the other hand, the students pinch the water lens, they will see a grid that looks similar to the right part of Figure 1.

We have not asked the students to diagnose what is really wrong with the lens. Instead we are just trying to get them to understand the basic principle. We can also look at the normal, near-sighted, and far-sightedness problems by moving the retina and the source of the light. This particular model is one that one can buy. It's made in Germany and has a syringe to push the water in or take the water out of the lens. Unfortunately, it is quite expensive but one can make something very similar to this for a very low cost by using a Styrofoam sphere and transparent plastic. [1,2]

The students do this hands-on part first. Then we introduce some of the physics concepts. To have the students understand the concepts better, together with our colleagues at Munich we developed two computer programs. One shows the ray tracing that one would use to understand simple vision and the problems introduced with nearsighted and farsighted eyes. A screen capture from this program is shown in Figure 3. With this program the students can move the object and the retina and they can place different lenses in front of the eye.

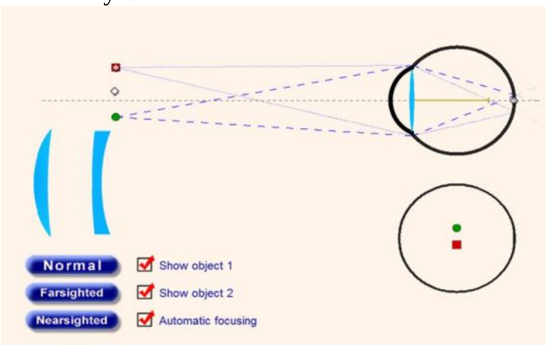

FIGURE 3. A screen capture from our optics of the eye interactive simulation.

A second program enables the students to manipulate variables in a situation similar to wavefront aberrometry. For the screen in Figure 4, the students can put the mouse cursor at the diamond-shaped object on the eye lens and push the lens in and out in the same way that they pushed the lens in and out with the physical model. When they do that they see changes in the grid at the bottom of the screen. They can also still pull the retina in and out to get nearsighted and farsighted eyes. Again, they will see how the grid changes. So the first part of the lesson is a hands-on activity, then we introduce some of the basic ideas, and then they go back and explain how it is that this system works by actually watching the ray tracing with a computer program.

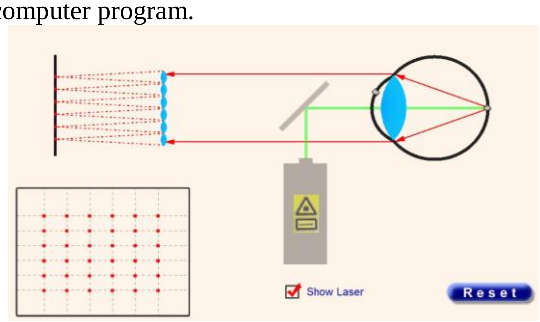

FIGURE 4: A screen capture from the interactive visualization on wavefront aberrometry.

At this time this program is basically done. The lessons are basically done and we've done the research. We did create two different versions of the lessons, one that uses models of the eye that one can buy from scientific companies or build oneself, but we also made a version that uses the more standard optical bench. We plan to get both the lesson and software up on our website rather soon.

SECOND EXAMPLE: MAGNETIC RESONANCE IMAGING

Our lesson on magnetic resonance imaging is not as complete as the wavefront aberrometry one but it is getting close. We have had problems with it in the research cycle and needed to start it over again. Part of the difficulty was the desire to teach the students about spin. However, we have never quite reached a comfortable approach for non-physics students.

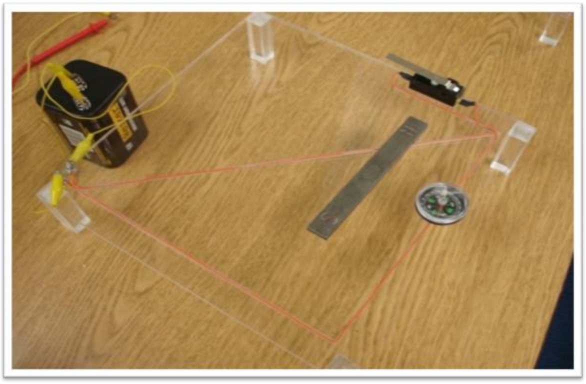

FIGURE 5: The apparatus for students to explore classical magnetic resonance of compasses.

The most recent version of the lesson begins with a rather classical experiment on magnetic resonance. Our apparatus (Figure 5) is a triangular shaped wire which has current in it. We put a bar magnet somewhere nearby to provide a constant magnetic field and then a compass which has no damping in it near the wire. The students turn the current on and off by pushing on a momentary switch. By turning the current on and off at an appropriate frequency, they can cause the compass to resonate. When they change the location of the bar magnet, they will discover that the resonant frequency changes. Thus, in some ways this observation is very similar to the process that goes on in magnetic resonance imaging.

For the version shown in Figure 6 we have included three compasses. Depending on where the bar magnet is placed relative to those three compasses, the students will find that each of them resonates at a different frequency of the current. Again, this is very similar to how the real MRI apparatus works.

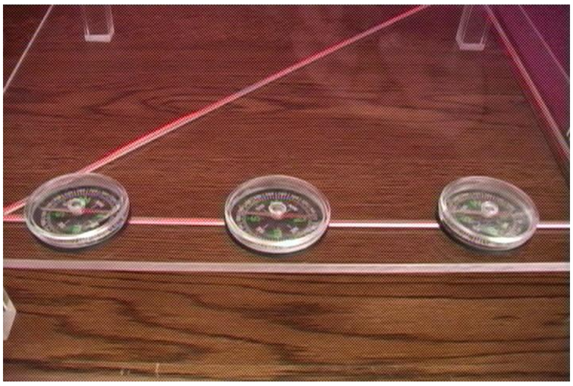

FIGURE 6: A close up of the apparatus for creating a resonance in the magnetic compasses.

The resonance experiment is the beginning of the lesson. We then introduce some of the underlying physics and conclude with a visualization. We are very fortunate that the physics education research group at the University of Colorado has created a rather nice visualization. A screen capture is shown in Figure 7.

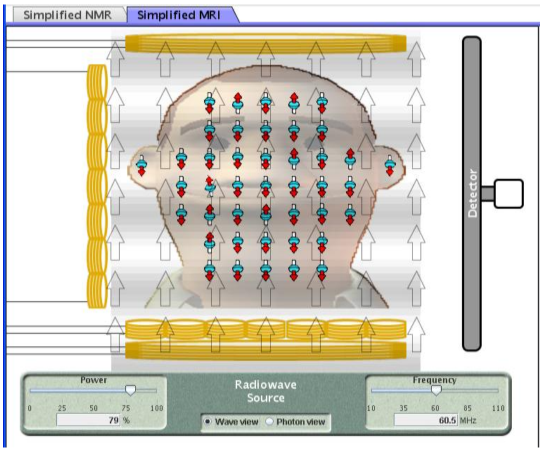

FIGURE 7: A screen capture of the MRI visualization. (Available from **http://phet.colorado.edu**.)

The screen shows the head of someone with a few magnets (protons) inside his head. The system basically works the same way as our currents, magnet, and compasses. Coils at the top and bottom create a static magnetic field. It is even possible to make the static magnetic field a gradient, so that it is greater at one end of the head than it is at the other. Additional coils provide the oscillating magnetic field. The students can see by using the variations in the power for the static magnetic field and variations in the frequency for the oscillating field when they reach a resonance. At that time many of the little magnets will flip back and forth.

To help the students understand it we help them make the connections between this visualization and the current-compass experiment. In this process we are treating the objects, the protons inside the person, as classical magnets. We have decided after several attempts at trying to do it with spin, that this approach is much more effective. It does not get us all the way toward how magnetic resonance images are really made. It does not involve, for example, the relaxation times which are quite important when computers are collecting all the data that they need to make an MRI image. But, it is a good first step to helping people understand how basic magnetism and the basic concepts of resonance are involved in the MRI process.

If one wants to go into more detail a large amount of materials are available free online, One that is particularly useful is The Basics of MRI at Rochester Institute of Technology. [3]

OTHER LESSONS BRIEFLY

Positron emission tomography (PET) is a relatively new imaging technique that is frequently used in combination with one of the other imaging methods. For a long time it was a clever idea that didn't seem to have much value in medical imaging although it was being used in basic brain research. The idea is that a positron emitter is injected into the body. The physician selects a chemical that is quite important for the body function or organ under investigation. That chemical is taken up by that organ. As the positrons are emitted, they find electrons very quickly and annihilate. Usually two 0.511 MeV gamma rays come out. Those gamma rays give a signal which then can be interpreted.

One of the differences between PET and the basic MRI or x-ray process is that PET involves the functions of the organ. The image is in part the result of how the positron emitting chemicals are interacting in organs in the body. Therefore one of PET's earliest uses was for brain imaging. Research was conducted using PET to learn how people's brain functions changed when they interacted with various things. For example, a rather clever study had people listen to different kinds of music and see which parts of their brains light up with the gamma rays depending on what kind of music they are listening to.

A lot of physics is involved in this process -- more physics than so far we have been able to deal with. We have really only delved into the very basics of distance, velocity, and time because in the coincidence experiments the most important point is what the time difference is between the two gamma rays hitting the detector. Then one can work backwards to figure out where the process actually started. To look at time-of-flight and coincidence we used a rather simple arrangement of two carts and a piece of cardboard that blocked a student's view. Then, another student released the carts from different locations. The student who could not see from where the carts were released was supposed to work backwards from the time difference between the two events coming out to the edge and determine where the carts were released. Thus, the students learn that from a rather simple time measurement they can reconstruct some information about an event that they cannot see.

In the second part of this lesson we used a cylinder that students could not see inside. Some LEDs were wired so that two of them came on each time the students pushed a switch. This process simulates two signals similar to two gamma photons reaching the detector. They are a coincidence set. The students draw lines for each pair of signals and discover the location of the source inside the cylinder source for each pair of signals must be. We have now created a computer version of this apparatus because the real one was rather fragile.

These activities are to teach the idea of time of flight and coincidence. These rather simple physics ideas are important in PET image reconstruction. At the end of the unit we give the students a problem where they get some data and they have to try to determine the location of the events. This is a paper and pencil test and it is our evaluation of how well the students are learning. We seem to be doing okay in terms of teaching the PET process.

SUMMARY

In each lesson these medical applications are relatively simple in terms of the physics involved. They can be easily applied to some understanding of modern medical imaging techniques. We feel that graphics, simulations, and analogies are all important. Our research so far has shown that all of them seem to be rather effective. We have placed all of the instructional materials, teachers' guides and software that we have developed ourselves plus links to ones that other people have developed on our website, http://web.phys.ksu.edu/mmmm/.

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REFERENCES

[1] Giuseppe Colicchia and Hartmut Wiesner, "Measuring aberration of the eye with wavefront technology," Physics Education **41** (4), 307-310 (2006).

[2] Giuseppe Colicchia, Hartmut Wiesner, Christina Waltner, and Dean Zollman, "A Model of the Human Eye," The Physics Teacher **46** (12), 528-531 (2008).

[3] Joseph P. Hornak, *The Basics of MRI*. http://www.cis.rit.edu/htbooks/mri/ (2006).