Intermediate Physics for Medicine and Biology: A Sampler

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Based on the blog hobbierothe.blogspot.com
Preface

I have collected 36 posts from hobbieroth.blogspot.com, a blog I started in 2007 as a way to promote a textbook Russ Hobbie and I wrote: *Intermediate Physics for Medicine and Biology*. I update the blog once a week, every Friday morning, like clockwork. Think of this collection as a quilt sampler: a six by six patchwork, with each block from a different pattern.

Some types of posts recur throughout the blog:

- book reviews,
- new homework problems,
- obituaries,
- comments on recent scientific articles,
- stories from my own research and life.

Some posts are mathematical, some contain extensive quotes from other sources, and some are meant to be funny. The most important ones are those that help students and instructors using *IPMB*.

If you want to read more, go to hobbieroth.blogspot.com and you will find over 500 posts.

Enjoy!

Brad Roth
December 21, 2017
Peter Basser wins ISMRM Gold Medal for Diffusion Tensor Imaging

Earlier this month, at the 16th Scientific Meeting and Exhibition of the International Society for Magnetic Resonance in Medicine (ISMRM) in Toronto, Peter Basser was awarded an ISMRM Gold Medal for "his pioneering and innovative scientific contributions in the development of Diffusion Tensor Imaging (DTI)."

Peter is an old friend of mine from the days when we were both staff fellows in the now-defunct Biomedical Engineering and Instrumentation Program at the National Institutes of Health in Bethesda, Maryland. We collaborated on many projects, including a study of magnetic stimulation of nerves (for example, see: Roth BJ, Basser PJ. "A model of the stimulation of a nerve-fiber by electromagnetic induction," IEEE Trans. Biomed. Eng., 37:588-597, 1990.)

Peter is now the head of the Section on Tissue Biophysics and Biomimetics, which is part of the Eunice Kennedy Shriver National Institute of Child Health and Human Development. The goal of his section is

"to understand fundamental physical mechanisms governing tissue-level physiological processes that are essential for life, or necessary to achieve a high quality of life. Examples include understanding the physical basis of nerve excitability and of effective load bearing in cartilage. This entails discovering relationships between physiological function and a tissue's structure, organization, and physical properties. This is done by studying the behavior of biological model systems using novel quantitative approaches (e.g., experimental methods, mathematical models, physical models). Another aim of ours is to transfer these new methodologies to the biomedical research and healthcare communities. An example includes the invention and successful dissemination of diffusion tensor magnetic resonance imaging from the 'bench' to the 'bedside'."

Diffusion Tensor Imaging is one of the topics that Russ Hobbie and I added to the 4th Edition of Intermediate Physics for Medicine and Biology (see Chap. 18, Sec. 13). We also wrote a new homework problem that asked the student to show that the trace of the diffusion tensor is independent of fiber direction. We had trouble deciding if this problem belonged in Chapter 4 (on diffusion) or Chapter 18 (on magnetic resonance imaging), and we ended up putting the problem in both chapters (see Problems 4.22 and 18.40). Another homework problem featuring Peter's work on cartilage appears in Chapter 5 (Problem 5.6).

The Office of NIH History has published an interview with Peter, in which he explains how he developed diffusion tensor imaging. Below is a brief excerpt of this interview, describing the moment Peter first conceived the idea of DTI (I make a cameo appearance):

"Actually, the first exposure I had to diffusion imaging was a talk that Denis Le Bihan had given. He had recently come to the NIH from France and talked about how diffusion could be used—I think it was in stroke—and I thought it was very interesting, but I didn't really
initially make a connection to it. But in the early 1990s, Denis Le Bihan and, I believe it was Philippe Douek had a poster presentation at one of the NIH research festivals off in a corner in one of the white tents that they had constructed over here in the parking lot East of Building 30. They had done something very novel. They had shown that they could color code different parts of the brain according to what they thought was the orientation of diffusion. That was a poster that resulted in a paper, I think early in the next year, by Denis and Philippe. But I visited that poster and I was there with my friend and colleague, Brad Roth, the guy I was doing the magnetic stimulation with, and I realized that there was something really fundamentally wrong with the approach that Denis and Philippe were using."

The rest, as they say, is history. One of Peter's first papers on DTI (Basser PJ, Mattiello J, LeBihan D. "MR Diffusion Tensor Spectroscopy and Imaging," Biophys. J., 66:259-267, 1994) has been cited over 700 times according to the ISI Web of Knowledge. His coauthors were Denis Le Bihan (a previous ISMRM Gold Medal Winner) and James Mattiello (the first graduate of the Oakland University Medical Physics PhD Program). The technique is now widely used to map fiber orientation in the brain and the heart.

Congratulations Peter!
Isaac Asimov

Isaac Asimov (1920-1992) was born 89 years ago today. He is best known as a science fiction writer, and is considered one of the "big three" of science fiction (along with Robert Heinlein and Arthur C. Clarke). He was also a great author of science popularizations, and wrote or edited over 500 books.

I started reading Asimov's nonfiction when in high school, and it had a big influence on me. In fact, one of the main reasons I decided to study science in college was because of his books. I particularly enjoyed his collections of essays originally published in *The Magazine of Fantasy and Science Fiction*. Asimov's writing covered all areas of science: biology, chemistry, physics, geology, astronomy, and medicine. My personal intellectual journey—from physics to biological physics to coauthor of the 4th Edition of *Intermediate Physics for Medicine and Biology*—began with the scientific liberal education he provided. When I was young, my goal was to read every book Asimov had ever written. I read scores of them, but soon I realized that he was writing them faster than I could read them.

Which of Asimov's books do I recommend? Among his fiction, I suggest *I, Robot* and the *Foundation Trilogy*. Unfortunately, his science popularizations are a bit dated now, but you might still enjoy many of his books, including his three-volume *Understanding Physics*, *The Genetic Code*, *The Wellsprings of Life*, *The Human Body*, and *The Human Brain*. For those wanting an Asimov sampler, try *Opus 100*, *Opus 200*, or *Opus 300*. Asimov aficionados will enjoy his two-volume autobiography *In Memory Yet Green* and *In Joy Still Felt*. The *Isaac Asimov Home Page* has much information including a complete list of his books. One obsessive Asimov fan provides summaries and reviews of all his work.

Readers of Intermediate Physics for Medicine and Biology may sometimes wonder how they will ever obtain the prerequisite background in physics, chemistry, biology and medicine necessary for such an interdisciplinary field of study. My solution was to start by reading Isaac Asimov. I don't know of any single author who could provide a better introduction to these topics.

Happy Birthday, Dr. Asimov. You left us too soon.
What’s Wrong With These Equations?

The 4th edition of Intermediate Physics for Medicine and Biology is full of equations: thousands of them. Each one must fit into the text in a way to make the book easy to read. How?

N. David Mermin wrote a fascinating essay that appeared in the October 1989 issue of Physics Today titled What’s Wrong With These Equations? You can find it online at www.cvpr.org/doc/mermin.pdf. It begins

“A major impediment to writing physics gracefully comes from the need to imbed in the prose many large pieces of raw mathematics. Nothing in freshman composition courses prepares us for the literary problems raised by the use of displayed equations.”

Mermin then presents three rules “that ought to govern the marriage of equations to readable prose”:

- Rule 1 (Fisher’s rule): Number all displayed equations.
- Rule 2 (Good Samaritan rule): When referring to an equation identify it by a phrase as well as a number.
- Rule 3 (Math is prose rule): End a displayed equation with a punctuation mark.

(In Intermediate Physics for Medicine and Biology, Russ Hobbie and I violate Fisher’s rule: some of our displayed equations are not numbered. All I can say is, there are lots of equations in our book, and revising it to obey Fisher’s rule would require more effort than we are willing to expend.) I know you are wondering how an essay about punctuating and numbering equations could possibly be interesting, but Mermin makes the subject entertaining. And if you ever find yourself writing an article that contains equations, obeying his three rules will make the article easier to read.

Many physicists know Mermin for his renowned textbook Solid State Physics with Neil Ashcroft. His series of “Reference Frame” essays in Physics Today are all delightful, particularly the ones with Professor Mozart. Several Reference Frame essays are reprinted in his book Boojums All the Way Through: Communicating Science in a Prosaic Age. The title essay describes Mermin’s quest to establish the whimsical word “Boojum” as a scientific term for a phenomenon in superfluidity. If you want to learn to write physics well, read Mermin.
Galileo's Daughter

As is my habit, I listen to recorded books when I walk my dog Suki each day. Recently, I listened to the book *Galileo's Daughter*, by Dava Sobel. I was surprised how touching I found this story (like Galileo, I have two daughters). It is a biography of Galileo Galilei (1564-1642), the famous Italian scientist, but also tells the parallel story of Sister Maria Celeste (1600-1634), Galileo’s daughter who was a nun at the San Matteo convent near Florence. The book quotes Maria Celeste’s letters to Galileo, which Sobel herself translated from Italian. (Unfortunately, Galileo’s replies are lost.) Maria Celeste comes across as a loving, intelligent and extremely loyal daughter who played a central role in Galileo’s life. “She alone of Galileo’s three children mirrored his own brilliance, industry, and sensibility, and by virtue of these qualities became his confidante.”

I tend to see biological physics everywhere, and I found some in this story. Late in his life, Galileo published his final book, *Two New Sciences*. One of these sciences was the motion of projectiles, and the other was what we would now call the strength of materials. In the part about materials, Galileo addressed the issue of scaling in animals. I quote Sobel, who quotes Galileo:

> “I have sketched a bone whose natural length has been increased three times and whose thickness has been multiplied until, for a correspondingly large animal, it would perform the same function which the small bone performs for its small animal. From the figures here shown you can see how out of proportion the enlarged bone appears. Clearly then if one wishes to maintain in a great giant the same proportion of limb as that found in an ordinary man he must either find a harder and stronger material for making the bones, or he must admit a diminution of strength in comparison with men of medium stature.”

(You can fine the picture of the two bones [here](#).) This example of how the strength of bones must scale with animal size did not make it into the 4th edition of *Intermediate Physics in Medicine and Biology*, although I sometimes discuss it when I teach PHY 325 (Biological Physics) at Oakland University. It serves as an excellent example of how physics can constrain the structure of animals. I won’t hold it against Galileo that he didn’t get his drawing of the bones quite right; it was the 17th century after all. According to Knut Schmidt-Nielsen (*Scaling: Why is Animal Size so Important*)

> “The need for a disproportionate increase in the size of supporting bones with increasing body size was understood by Galileo Galilei (1637), who probably was the first scientist to publish a discussion of the effects of body size on the size of the skeleton. In his Dialogues [Two New Sciences was written in the form of a dialogue] he mentioned that the skeleton of a large animal must be strong enough to support the weight of the animal as it increases with the third power of the linear dimensions. Galileo used a drawing to show how a large bone is disproportionately thicker than a small bone. (Incidentally, judging from the drawing, Galileo made an arithmetical mistake. The larger bone, which is three times as long as the shorter, shows a 9-fold increase in diameter, which is a greater distortion than required. A three-fold increase in linear dimensions should give a 27-fold increase in mass,
and the cross-sectional area of the bone should be increased 27-fold, and its diameter therefore by the square root of 27 (i.e., 5.2 instead of 9))."

Russ Hobbie and I discuss the issue of scaling in Chapter 2 of Intermediate Physics for Medicine and Biology. In Problem 28 of Chapter 2, we ask the reader to calculate the falling speed of animals of different sizes, taking into account air friction. The solution to the problem indicates that large animals, with their smaller surface-to-volume ratio, have a larger terminal speed (the speed of descent in steady state, once the acceleration drops to zero) than smaller animals. We end the problem with one of my favorite quotes, by J. B. S. Haldane

“You can drop a mouse down a thousand-yard mine shaft; and arriving at the bottom, it gets a slight shock and walks away. A rat is killed, a man is broken, a horse splashes.”

When listening to Galileo’s Daughter, I was surprised to hear Galileo’s own words on this same subject, which are quite similar and written centuries earlier.

“Who does not know that a horse falling from a height of three or four braccia will break his bones, while a dog falling from the same height or a cat from eight or ten, or even more, will suffer no injury? Equally harmless would be the fall of a grasshopper from a tower or the fall of an ant from the distance of the Moon.”

Of course, the climax of the Galileo’s Daughter is the great scientist’s trial by the Catholic Church for publishing a book supporting the Copernican view that the earth travels around the sun. Although I was familiar with this trial, I had never read the transcript, which Sodal quotes extensively. Listening to the elderly Galileo being forced into a humiliating recantation of his scientific views almost made me nauseous.

Sobel is a fine writer. Years ago I read her most famous book, Longitude, about finding a method to measure longitude at sea. Galileo himself contributed to the solution of this problem by introducing a method based on the orbits of the moons of Jupiter, which he of course discovered. However, the longitude problem was not definitely solved until clocks that could keep time on a rolling ship were invented by John Harrison. I have also listened to Sobel’s book The Planets, which I enjoyed but, in my opinion, isn’t as good as Longitude and Galileo’s Daughter. I hope Sobel continues writing books. As soon as a new one comes out (and arrives at the Rochester Hills Public Library, because I’m too cheap to buy these audio books), Suki and I plan on taking some long walks. I can’t wait.
Friday, June 18, 2010

Myopia

Section 14.12 in the 4th edition of *Intermediate Physics for Medicine and Biology* discusses the physics of the eye. One topic related to vision that I have always found fascinating is myopia:

“In nearsightedness or *myopia*, parallel rays come to a focus in front of the *retina*. The eye is slightly too long for the shape of the *cornea* […] The total *converging power* of the eye is too great, and the relaxed eye focuses at some closer distance, from which the rays are diverging. *Accommodation* can only increase the converging power of the eye, not decrease it, so the unassisted myopic eye cannot focus on distant objects. Myopia can be corrected by placing a *diverging spectacle* or *contact lens* in front of the eye, so that incoming parallel rays are diverging when the strike the cornea.”

The interesting thing about myopia is that, in contrast to far-sightedness (*hypermetropia*), you cannot correct it by accommodation. Before the invention of *eye glasses* in the late *Middle Ages*, if you were born with myopia then distant objects would always be a blur.

When teaching Biological Physics (PHY 325) at *Oakland University*, I often end my discussion of myopia with a quote from David McCullough’s wonderful biography of Theodore Roosevelt, *Mornings on Horseback*. Roosevelt suffered from myopia and didn’t get his first glasses until he was a teenager. McCullough tells the story:

“Then, at a stroke, the summer of 1872, he was given a gun and a large pair of spectacles and nothing had prepared him for the shock, for the infinite difference in his entire perception of the world about him or his place in it.

The gun was a gift from Papa—a 12-gauge, double-barreled French-made (*Lefaucheux*) *shotgun* with a lot of *kick* and of such simple, rugged design that it could be hammered open with a brick if need be, the ideal gun for an awkward, frequently absent-minded thirteen-year-old. But blasting away with it in the woods near *Dobbs Ferry* he found he had trouble hitting anything. More puzzling, his friends were constantly shooting at things he never even saw. This and the fact that they could also read words on billboards that he could barely see, he reported to his father, and it was thus, at summer’s end, that the spectacles were obtained.

They transformed everything. They ‘literally opened an entirely new world to me,’ he wrote years afterward, remembering the moment. His range of vision until then had been about thirty feet, perhaps less. Everything beyond was a blur. Yet neither he nor the family had sensed how handicapped he was. ‘I had no idea how beautiful the world was…I could not see, and yet was wholly ignorant that I was not seeing.’

How such a condition could possibly have gone undetected for so long is something of a mystery, but once discovered it did much to explain his awkwardness and the characteristic detached look he had, those large blue eyes ‘not looking at anything present.’ “
I am a lover of history and a big fan of David McCullough. A couple of his books with a scientific or engineering bent are Path Between the Seas: The Creation of the Panama Canal and The Great Bridge: The Epic Story of the Building of the Brooklyn Bridge. His purely historical books, such as 1776 and John Adams, are also excellent.

To learn more, see the information about myopia on the website for the American Optometric Association. An modern option for correcting myopia that was not available in Roosevelt’s time is laser surgery to reshape the cornea.
Friday, July 9, 2010

**Paris**

I just returned from a vacation in Paris, where my wife and I celebrated our 25th wedding anniversary. Russ Hobbie was there at the same time, although conflicting schedules did not allow us to get together. My daughter Katherine posted the blog entries for the last two weeks, when I had limited computer access. Thanks, Kathy.

Although most of our time was spent doing the usual tourist activities (for example, the Arc de Triomphe, the Notre Dame Cathedral, Versailles, and, my favorite, a dinner cruise down the Seine), I did keep my eye open for those aspects of France that might be of interest to readers of the 4th edition of Intermediate Physics for Medicine and Biology. We visited the Pantheon, where we saw the tomb of Marie Curie (a unit of nuclear decay activity, the curie, was named after her and is discussed on page 489 of Intermediate Physics for Medicine and Biology). Marie Curie lies next to her husband Pierre Curie (of the Curie temperature, page 216). Also in the Pantheon is Jean Perrin, who determined Avogadro’s number (see the footnote on page 85) and Paul Langevin, of the Langevin equation (page 87). Hanging from the top of the dome is a Foucault pendulum, in the exact place where Leon Foucault publicly demonstrated the rotation of the earth in 1851. I like it when physics takes center stage like that.

Another scientific site we visited is a museum honoring Louis Pasteur at the Pasteur Institute. Pasteur chose to be buried in his home (now the museum) rather than in the Pantheon. Readers of Intermediate Physics for Medicine and Biology will find him to be an excellent example of a researcher who bridges the physical and biological sciences. His first job was as a professor of Physics, although he would probably be considered more of a chemist that a physicist. His early work was on chiral molecules and how they rotated light. He later became famous for his research on the spontaneous generation of life and a vaccine for rabies. In his book Adding A Dimension, Isaac Asimov lists Pasteur as one of the ten greatest scientists of all time. The museum is enjoyable, although it is not as accessible to English speakers as some of the larger museums such as the Louvre and the delightful Musee d’Orsay. Because I speak no French, I had a difficult time following many of the Pasteur exhibits. Also at the museum was a nice display about microbiologist Jacques Monod, who I will discuss in a future entry to this blog.

The only other French scientist on Asimov’s top-ten list was the chemist Antoine Lavoisier. Oddly, the French don’t seem to celebrate Lavoisier’s accomplishments as much as you might expect. (Beware, my conclusion is based on a brief 2-week vacation, and I may have missed something.) Perhaps his death by the guillotine during the French revolution has something to do with it. We visited the Place de la Concorde, where Lavoisier was beheaded. In A Short History of Chemistry, Asimov writes

"In 1794, then, this man [Lavoisier], one of the greatest chemists who ever lived, was needlessly and uselessly killed in the prime of life. ‘It required only a moment to sever that head, and perhaps a century will not be sufficient to produce another like it,’ said Joseph Lagrange, the great mathematician. Lavoisier is universally remembered today as ‘the father of modern chemistry.’ "
I normally associate Leonardo da Vinci with Italy, but when touring the Chateau at Amboise in the Loire Valley, we stumbled unexpectedly upon his grave. He spent the last three years of his life in France. We toured an excellent museum dedicated to da Vinci, containing life-size reconstructions of some of his engineering inventions. Although da Vinci had many interests and may be best known for his paintings (yes, I saw the Mona Lisa while at the Louvre), at least some of his work might be called biomedical engineering, such as his work on an underwater breathing apparatus and on human flight.

Seventy-two famous French scientists and mathematicians are listed on the Eiffel Tower, including Laplace (of the Laplacian, page 91), Ampere (of Ampere’s law, page 206, and the unit of current, page 145), Navier (of the Navier-Stokes equation, page 27), Legendre (of Legendre polynomials, page 184), Becquerel (of the unit of activity, page 489), Fresnel (of the Fresnel zone for diffraction, page 352), Coulomb (of the unit of charge and Coulomb’s law, both on page 137), Poisson (of Poisson’s ratio, page 27; the Poisson-Boltzmann equation, page 230; and the Poisson probability distribution, page 572), Clapeyron (of the Clausius-Clapeyron relation, page 78), and Fourier (of the Fourier series, page 290). I could not see all these names because the tower was partially covered for painting. Note that Lavoisier was included on the Eiffel Tower, but Poiseuille (of Poiseuille flow, page 17) was not. The view from the top of the tower is spectacular.

I admit, I am not the best of travelers and am glad to be home in Michigan. But I believe there is much in France that readers of Intermediate Physics for Medicine and Biology will find interesting.
The leibniz

In order to motivate the study of thermal physics, Chapter 3 of the 4th edition of Intermediate Physics for Medicine and Biology begins with an examination of how many equations are required to simulate the motion of all the molecules in one cubic millimeter of blood. Russ Hobbie and I write

“It is possible to identify all the external forces acting on a simple system and use Newton’s second law \((\mathbf{F} = m\mathbf{a})\) to calculate how the system moves … In systems of many particles, such calculations become impossible. Consider, for example, how many particles there are in a cubic millimeter of blood. Table 3.1 shows some of the constituents of such a sample [including \(3.3 \times 10^{19}\) water molecules]. To calculate the translational motion in three dimensions, it would be necessary to write three equations for each particle using Newton’s second law. Suppose that at time \(t\) the force on a molecule is \(\mathbf{F}\). Between \(t\) and \(t + \Delta t\), the velocity of the particle changes according to the three equations

\[
v_i(t + \Delta t) = v_i(t) + F_i \Delta t/m, \quad (i = x, y, z),
\]

The three equations for the change of position of the particle are of the form \(x(t + \Delta t) = x(t) + v_x(t) \Delta t\). Solving these equations requires at least six multiplications and six additions for each particle. For \(10^{19}\) particles, this means about \(10^{20}\) arithmetic operations per time interval … It is impossible to trace the behavior of this many molecules on an individual basis.

Nor is it necessary. We do not care which water molecule is where. The properties of a system that are of interest are averages over many molecules: pressure, concentration, average speed, and so forth. These average macroscopic properties are studied in statistical or thermal physics or statistical mechanics.”

It is difficult to gain an intuitive feel for just how many differential equations are needed in such a calculation, just as it is difficult to imagine just how many molecules make up a macroscopic bit of matter. Chemists have solved the problem of dealing with large numbers of molecules by introducing the unit of a mole, corresponding to Avogadro’s number \((6 \times 10^{23})\) of molecules. Other quantities involving Avogadro’s number are similarly defined. For instance, the Faraday corresponds to the magnitude of the charge of one mole of electrons (I admit, the Faraday is more of a constant than a unit); see page 60 and Eq. 3.32 of Intermediate Physics for Medicine and Biology. In Problem 2 of Chapter 14, Russ and I discuss the einstein, a unit corresponding to a mole of photons. When doing large-scale numerical simulations on a computer, it would be useful to have a similar unit to handle very large numbers of differential equations, such as are required to model a drop of blood.

Fortunately, such a unit exists, called the leibniz. Sui Huang and John Wikswo coined the term in their paper Dimensions of Systems Biology, published in the Reviews of Physiology, Biochemistry & Pharmacology (Volume 157, Pages 81-104, 2006). They write
“The electrical activity of the heart during ten seconds of fibrillation could easily require solving $10^{18}$ coupled differential equations (Cherry et al. 2000). (N.B., Avogadro’s number of differential equations may be defined as one Leibnitz, so 10 s of fibrillation corresponds to a micro-Leibnitz problem.) Multiprocessor supercomputers running for a month can execute a micromole of floating point operations, but in the cardiac case such computers may run several orders of magnitude slower than real time, such that modeling 10 s of fibrillation might require 1 exaFLOP/year.”


“What distinguishes the models of systems biology from those of many other disciplines is their multiscale richness in both space and time: these models may eventually have millions of dynamic variables with complex non-linear interactions. It is conceivable that the ultimate models for systems biology might require a mole of differential equations (called a Leibnitz) and computations that require a yottaFLOPs (floating point operations per second) computer.”

If we take the leibniz (Lz) as our unit of simulation complexity, the calculation Russ and I consider at the start of Chapter 3 requires solving approximately $6 \times 10^{19}$ differential equations, or about 0.1 mLz. Note that we describe two first order differential equations for each molecule, but others might prefer to speak of a single second-order differential equation. This would make a difference of a factor of two in the number of equations. I propose that when using the leibniz we consider only first order ODEs. Moreover, when using a differential equation governing a vector, we count one equation per component.

For those not familiar with Gottfried Leibniz (1646 – 1716), he is a German mathematician and a co-inventor of the calculus, along with Isaac Newton. In fact, Leibniz and Newton got into one of the biggest priority disputes in the history of science about this landmark development. Newton has his unit, so it’s only fair that Leibniz has one too. Leibniz also made contributions to information theory and computational science, so the liebniz is a particularly appropriate way to honor this great mathematician.

John Wikswo, my PhD advisor when I was in graduate school at Vanderbilt University, notes that there are two alternative spellings of Leibniz's name: Leibnitz and Leibniz. I favor “Leibniz”, the spelling on Wikipedia, and so does Wikswo now, but he points out that there’s plenty of support for “Leibnitz” used in his earlier publications. I had high hopes of enjoying a bit of fun at my friend’s expense by adding an annoying “[sic]” after each appearance of “Leibnitz” in the above quotes, but then Wikswo pointed out that Richard Feynman used “Leibnitz” in the Feynman Lectures on Physics. What can I say; you can’t argue with Feynman.
Destiny of the Republic

Regular readers of this blog know that I am in the habit of listening to audio books while I take my dog Suki on her daily walks. My tastes lean toward science, history, and biography, and I always keep a watch out for biological or medical physics in these books. Over the Christmas break, I listened to Destiny of the Republic: A Tale of Madness, Medicine and the Murder of a President, by Candice Millard, about the assassination of President James Garfield in 1881, shot by madman Charles Guiteau.

The book tells the fascinating story of Garfield’s nomination at the Republican National Convention in 1880, back in a time when conventions were less choreographed and predictable than they are today. Garfield nominated his fellow Ohioan John Sherman (General William Tecumseh Sherman’s brother), who was running against Senator James Blaine and former president Grant. After many ballots in which no nominee obtained a majority, the delegates turned to Garfield as their compromise choice. After being chosen the Republican nominee, he defeated Democrat and former Civil War general Winfield Scott Hancock in the general election.

A few months after being sworn in, Garfield was shot by Guiteau, who had applied for a job in the new administration but had been turned down. The bullet did not kill Garfield immediately, and he lingered on for weeks. At this point, medical physics enters the story through one of the book’s subplots about the career of Alexander Graham Bell, inventor of the telephone. Millard tells the tale of how Bell set up one of his early telephones for demonstration at the 1876 Centennial Exposition, but was ignored until a chance meeting with his acquaintance, Emperor Pedro II of Brazil, who drew attention to Bell’s display. Upon hearing that the President had been shot, Bell quickly invented a metal detector with the goal of locating the bullet still lodged in Garfield’s abdomen. The detector is based on the principle of electromagnetic induction, discussed in Section 8.6 of the 4th edition of Intermediate Physics for Medicine and Biology. A changing magnetic field induces eddy currents in a nearby conductor. These eddy currents produce their own magnetic field, which is then detected. Essentially, the device monitored changes in the inductance of the metal detector caused by the bullet. Such metal detectors are now common, particularly for nonmedical uses such as searching for metal objects buried shallowly in the ground. At the time, the device was rather novel. Michael Faraday (and, independently, Joseph Henry) had discovered electromagnetic induction in 1831, and Maxwell’s equations summarizing electromagnetic theory were formulated by James Maxwell in 1861, only twenty years before Garfield’s assassination. Being a champion of medical and biological physics, I wish I could say that Bell’s invention saved the president’s life, or at least had a positive effect during his treatment. Unfortunately, it did not, in part because of interference from metal springs in the mattress Garfield laid on, but mainly because the primary physician caring for Garfield, Dr. Willard Bliss, insisted that Bell only search the right side of the body where he believed the bullet was located, when in fact it was on the unexplored left side.

Another issue discussed in the book is the development of antiseptic methods in medicine, pioneered by Joseph Lister in the 1860s. Apparently the direct damage caused by the bullet was not life-threatening, and Millard suggests that if Garfield had received no treatment whatsoever
for his wounds, he would have likely survived. Unfortunately, the doctors of that era, being skeptical or hostile to Lister’s new ideas, probed Garfield’s wound with various non-sterile instruments, including their fingers. Garfield died of an infection, possibly caused by these actions.

I enjoyed Millard’s book, and came away with a greater respect for President Garfield. Bell’s metal detector was used to locate bullets in injured soldiers throughout the rest of the 19th century, until x rays became the dominant method for finding foreign objects. It is an early example of the application of electricity and magnetism to medicine.

Click here to listen to Candice Millard speak about her book.
The Intermediate Physics for Medicine and Biology Tourist

Over the Christmas break I was browsing through the Guidebook for the Scientific Traveler: Visiting Physics and Chemistry Sites Across America, and it got me to wondering what sites a reader of the 4th edition of Intermediate Physics for Medicine and Biology might want to visit. Apparently having too much time on my hands, I devised a trip through the United States for our readers. (Perhaps I’ll prepare an international edition later.) The trip starts and ends in Rochester, Michigan, where I work, but the path consists of a large circle and you can begin anywhere. I have not visited all these places, but I know enough about them to suspect you would enjoy them all. Tell me if I have forgotten any important sites. Happy travels!

**Oakland University in Rochester, Michigan.** OU is home to Intermediate Physics for Medicine and Biology (IPMB) coauthor Brad Roth, in the Department of Physics. Here Roth collaborated with Russ Hobbie to prepare the 4th edition of IPMB.

**The University of Chicago in Chicago, Illinois.** The elementary charge (the magnitude of the charge of an electron, mentioned in IPMB in Chapter 3 and many times later) was first measured accurately by Robert Millikan at the University of Chicago using his famous oil drop experiment. The American Physical Society has an initiative to present commemorative plaques at important sites in the history of physics. Be sure to visit the Millikan plaque. You can see the original equipment used by Millikan at Chicago’s wonderful Museum of Science and Industry. Chapter 1 of IPMB cites the book Powers of Ten by Phillip and Phylis Morrison and the office of C. & R. Eames. The book is centered on a couple picnicking in Chicago, near Soldier Field and the Shedd Aquarium. Be sure to stop there, with your copy of Powers of Ten in hand.

**Morrison, Illinois.** Robert Millikan was born in Morrison, and a downtown park in this small town about 120 miles west of Chicago bears his name (although there is no sign or marker to indicate it). IPMB coauthor Brad Roth grew up in Morrison.

**University of Minnesota, in Minneapolis, Minnesota.** IPMB’s author Russ Hobbie worked at the University of Minnesota for years, and remains an emeritus faculty member in the Department of Physics and Astronomy. Stop by and visit him in nearby Saint Paul. While in Minneapolis, be sure to visit the Bakken Museum, perhaps the only museum in the country dedicated entirely to electricity and magnetism, and especially bioelectricity and biomagnetism, as discussed in Chapters 6-9 of IPMB. Earl Bakken was one of the founders of the medical device company Medtronic. Stop by at Medtronic's nearby Mounds View Bakken Education Center.

**University of California Berkeley, in Berkeley, California.** The cyclotron, crucial for nuclear medicine (see Chapter 17 of IPMB), was invented by Ernest Lawrence at UC Berkeley. See the APS plaque commemorating this invention. Material from a cyclotron in Lawrence’s lab led to the discovery of technetium, an element with no stable isotopes that is widely used in nuclear medicine imaging and is discussed at length in Chapter 17 of IPMB. While in the San Francisco area, visit Stanford University where Felix Bloch performed his pioneering experiments in
nuclear magnetic resonance (Chapter 18, IPMB), and where Mark Denny has his Biomechanics Laboratory (Denny’s book Air and Water is cited often in IPMB). Don’t forget to visit the Exploratorium.

California Institute of Technology, in Pasadena, California. Carl Anderson discovered positrons while working at CalTech (see the APS plaque for Anderson’s discovery). Positrons are used in positron emission tomography (PET) imaging (Chapter 17, IPMB). Also from Cal Tech in Richard Feynman, whose Lectures on Physics are cited in IPMB.

Washington University in St Louis, in St Louis, Missouri. Arthur Compton performed his groundbreaking experiments on Compton Scattering (Chapter 15, IPMB) at Washington University. See the APS plaque commemorating his work. Their biomedical engineering department now is home to many leading researchers in cardiac electrophysiology, including post doc Debbie Janks, a reader and often a commenter on the IPMB facebook group and blog.

Vanderbilt University, in Nashville, Tennesse. IPMB coauthor Brad Roth attended graduate school at Vanderbilt, working with John Wikswo in the Department of Physics and Astronomy. There, they measured the magnetic field of a single nerve axon, as described in Chapter 8 of IPMB. IPMB author Russ Hobbie was a Visiting Professor at Vanderbilt in 1999. Max Delbruck, an early biological physicist who contributed to our understanding of genetics, performed many of his Nobel Prize winning experiments at Vanderbilt.

Duke University, in Durham, North Carolina. Duke’s Department of Biomedical Engineering has been the home of many leaders in bioelectricity and cardiac electrophysiology, including Robert Plonsey, whose books are often cited often in IPMB. The Duke Biology Department is home to Steven Vogel, author of Life in Moving Fluids, another book cited in IPMB. Be sure to find the statue of former Duke physiologist Knut Schmidt-Nielsen studying a camel, which graces the Duke campus.

National Institutes of Health, in Bethesda, Maryland. No tour of biomedical facilities in the United States would be complete without stopping at the NIH campus in Bethesda. Be sure to visit the Stetton Museum of Medical Research in Building 10; the Warren Grant Magnuson Clinical Center. Stop by Building 13 and see where IPMB coauthor Brad Roth worked on transcranial magnetic stimulation (IPMB, Chapter 8) and where his friend Peter Basser invented MRI Diffusion Tensor Imaging (IPMB, Chapter 18) (Peter’s office is still there; stop by and say hi). You could spend a week visiting all the historic medical research sites in the Washington DC area.

Yale University, in New Haven, Connecticut. Visit Yale and walk the path of the early American physicist Josiah Williard Gibbs, whose work on chemical thermodynamics is discussed in Chapter 3 of IPMB, including the Gibbs Free Energy. See the APS plaque commemorating Gibbs’ work.

Framingham, Massachusetts. Visit the town that contributed more to uncovering the diseases of the heart than any other, through the Framingham Heart Study. Framingham is one of the few locations mentioned explicitly in IPMB, in Chapter 2.
**Harvard University, in Cambridge, Massachusetts.** Edward Purcell performed his early experiments on nuclear magnetic resonance at Harvard, which resulted in the Nobel Prize. He is also author of a beloved paper cited in IPMB, *Life at Low Reynolds Number*. Visit the site of the Harvard cyclotron, where IPMB author Russ Hobbie was a graduate student, and where Allan Cormack worked on the mathematical methods underlying computed tomography (IPMB, Chapter 16). Visit the nearby Massachusetts Institute of Technology Museum, containing a collection of artifacts related to science and technology (IPMB author Russ Hobbie obtained his undergraduate degree from MIT). While near Boston, visit the Museum of Science, especially their *Theater of Electricity*.

**Woods Hole Marine Biological Laboratories, in Woods Hole, Massachusetts.** At Woods Hole, Kenneth Cole developed the voltage clamp method (Chapter 6, IPMB), which played an important role in the discovery of how nerves conduct action potentials. Stop by the Visitors Center and take a tour.

**Oakland University, in Rochester Michigan.** Back to the starting point. Be sure to stop by Brad Roth’s office (166 Hannah Hall) and see his collection of all four editions of IPMB sitting on his bookshelf.
Andrew Huxley (1917-2012)

Andrew Huxley, the greatest mathematical biologist of the 20th century, died on Wednesday, May 30. Huxley won the Nobel Prize for his groundbreaking work with Alan Hodgkin that explained electrical transmission in nerves.


"Considerable work was done on nerve conduction in the late 1940s, culminating in a model that relates the propagation of the action potential to the changes in membrane permeability that accompany a change in voltage. The model [Hodgkin and Huxley (1952)] does not explain why the membrane permeability changes; it relates the shape and conduction speed of the impulse to the observed changes in membrane permeability. Nor does it explain all the changes in current…Nonetheless, the work was a triumph that led to the Nobel Prize for Alan Hodgkin and Andrew Huxley."

The paper we cite (A Quantitative Description of Membrane Current and its Application to Conduction and Excitation in Nerve, Journal of Physiology, Volume 117, Pages 500-544) is one of my favorites. Whenever I teach biological physics, I assign this paper to my students as an example of mathematical modeling in biology at its best. In 1981 Hodgkin and Huxley wrote a "citation classic" article about their paper, which has now been cited over 9300 times. They concluded

"Another reason why our paper has been widely read may be that it shows how a wide range of well-known, complicated, and variable phenomena in many excitable tissues can be explained quantitatively by a few fairly simple relations between membrane potential and changes of ion permeability—processes that are several steps away from the phenomena that are usually observed, so that the connections between them are too complex to be appreciated, intuitively. There now seems little doubt that the main outlines of our explanation are correct, but we have always felt that our equations should be regarded only as a first approximation that needs to be refined and extended in many ways in the search for the actual mechanism of the permeability changes on the molecular scale."

As one who does mathematical modeling of bioelectric phenomena for a living, I can think of no better way to honor Huxley than to show you his equations:
This set of four nonlinear ordinary differential equations, plus six expressions relating how the ion channel rate constants depend on voltage, not only describes the membrane of the squid giant nerve axon, but is the starting point for models of all electrically active tissue. Russ and I consider this model to be so important that we dedicate six pages to exploring it, and present in our Fig. 6.38 a computer program to solve the equations. For anyone interested in electrophysiology, becoming familiar with the Hodgkin-Huxley model is job one, just as analyzing the Bohr model for hydrogen is the starting point for someone interested in atomic structure. Remarkably, 60 years ago Huxley solved these differential equations numerically using only a hand-crank adding machine.

How can you learn more about this great man? First, the Nobel Prize website contains his biography, a transcript of his Nobel lecture, and a video of an interview. Another recent, more detailed interview is available on youtube in two parts, part 1 and part 2. Huxley wrote a fascinating description of the many false leads during their nerve studies in a commemorative article celebrating the 50th anniversary of his famous paper. Finally, the Guardian published an obituary of Huxley yesterday.

I will conclude by quoting the summary at the end of Hodgkin and Huxley’s 1952 paper, which was the last of a series of five articles describing their voltage clamp experiments on a squid axon.

**SUMMARY**

1. The voltage clamp data obtained previously are used to find equations which describe the changes in sodium and potassium conductance associated with an alteration of membrane potential. The parameters in these equations were determined by fitting solutions to the experimental curves relating sodium or potassium conductance to time at various membrane potentials.
2. The equations, given on pp. 518-19, were used to predict the quantitative behaviour of a model nerve under a variety of conditions which corresponded to those in actual experiments. Good agreement was obtained in the cases:
   (a) The form, amplitude and threshold of an action potential under zero membrane current at two temperatures.
   (b) The form, amplitude and velocity of a propagated action potential.
(c) The form and amplitude of the impedance changes associated with an action potential.
(d) The total inward movement of sodium ions and the total outward movement of potassium ions associated with an impulse.
(e) The threshold and response during the refractory period.
(f) The existence and form of subthreshold responses.
(g) The existence and form of an anode break response.
(h) The properties of the subthreshold oscillations seen in cephalopod axons.

3. The theory also predicts that a direct current will not excite if it rises sufficiently slowly.
4. Of the minor defects the only one for which there is no fairly simple explanation is that the calculated exchange of potassium ions is higher than that found in Sepia axons.
5. It is concluded that the responses of an isolated giant axon of Loligo to electrical stimuli are due to reversible alterations in sodium and potassium permeability arising from changes in membrane potential.
Friday, October 19, 2012

**Ernest Rutherford**

Who is the greatest physicist never mentioned by name in the 4th edition of *Intermediate Physics for Medicine and Biology*? Russ Hobbie and I allude to Newton, Maxwell, Faraday, Bohr, Einstein, and many others. But a search for the name “Rutherford” comes up empty. In my opinion, Ernest Rutherford is the greatest physicist absent from our book. Ironically, he is also one of my favorite physicists; a colorful character who rivals Faraday as the greatest experimental scientist of all time.

Rutherford (1871-1937) was born in New Zealand, and attended Cambridge University in England on a scholarship. His early work was on radioactivity, a subject discussed in Chapter 17 of our textbook. *Asimov’s Biographical Encyclopedia of Science and Technology* states

“[Rutherford] was one of those who, along with the Curies, had decided that the rays given off by radioactive substances were of several different kinds. He named the positively charged ones alpha rays and the negatively charged ones beta rays….Between 1906 and 1909 Rutherford, together is his assistant, Geiger, studied alpha particles intensively and proved quite conclusively that the individual particle was a helium atom with its electrons removed.

Rutherford’s interest in alpha particles led to something greater still. In 1906, while still at McGill in Montreal, he began to study how alpha particles are scattered by thin sheets of metal….From this experiment Rutherford evolved the theory of the nuclear atom, a theory he first announced in 1911….

For working out the theory of radioactive disintegration of elements, for determining the nature of alpha particles, [and] for devising the nuclear atom, Rutherford was awarded the 1908 Nobel Prize in chemistry, a classification he rather resented, for he was a physicist and tended to look down his nose at chemists….

Rutherford was … the first man ever to change one element into another as a result of the manipulations of his own hands. He had achieved the dream of the alchemists. He had also demonstrated the first man-made ‘nuclear reaction’…

He was buried in Westminster Abbey near Newton and Kelvin.”

Rutherford also measured the size of the nucleus. To explain his alpha particle scattering experiments, he derived his famous scattering formula (see Chapter 4 of *Eisberg and Resnick* for details). He found that his formula worked well except when very high energy alpha particles are fired at low atomic-number metal sheets. For instance, results began to deviate from his formula when 3 MeV alpha particles are fired at aluminum. The homework problem below explains how to estimate the size of the nucleus from this observation. This problem is based on data shown in Fig. 4-7 of Eisberg and Resnick’s textbook.
Section 17.1

**Problem ½** An alpha particle is fired directly at a stationary aluminum nucleus. Assume the only interaction is the electrostatic repulsion between the alpha particle and the nucleus, and the aluminum nucleus is so heavy that it is stationary. Calculate the distance of their closest approach as a function of the initial kinetic energy of the alpha particle. This calculation is consistent with Ernest Rutherford’s alpha particle scattering experiments for energies lower than 3 MeV, but deviates from his experimental results for energies higher than 3 MeV. If the alpha particle enters the nucleus, the nuclear force dominates and the formula you calculated no longer applies. Estimate the radius of the aluminum nucleus.

To learn more about Ernest Rutherford and his groundbreaking experiments, I recommend the book *Rutherford: Simple Genius* by David Wilson.

In addition to his fundamental contributions to physics, I have a personal reason for liking Rutherford. Academically speaking, he is my great-great-great-great grandfather. My PhD advisor was John Wikswo, who got his PhD working under William Fairbank at Stanford. Fairbank got his PhD under Cecil Lane, who studied under Etienne Bieler, who worked for James Chadwick (discoverer of the neutron), who was a student of Rutherford’s.

Ernest Rutherford died (needlessly) on October 19, 1937; 75 years ago today.
The Sinogram

I love sinograms. They are rare and fascinating mixtures of science and art, and often are quite beautiful. One should be able to look at a sinogram and intuitively picture the two-dimensional image. Unfortunately, I rarely can do this, except for the most simple examples.

Russ Hobbie and I define the sinogram in the 4th edition of Intermediate Physics for Medicine and Biology. We explain how to calculate the projection, $F(\theta, x')$, from the image, $f(x,y)$. This transformation and its inverse—determining $f(x,y)$ from $F(\theta, x')$—is at the heart of many imaging algorithms, such as those used in computed tomography.

“The process of calculating $F(\theta, x')$ from $f(x, y)$ is sometimes called the Radon transformation. When $F(\theta, x')$ is plotted with $x'$ on the horizontal axis, $\theta$ on the vertical axis, and $F$ as the brightness or height on a third perpendicular axis, the resulting picture is called a sinogram. For example, the projection of $f(x, y) = \delta(x - x_0)\delta(y - y_0)$ is $F(\theta, x') = \delta(x' - (x_0 \cos \theta + y_0 \sin \theta))$. A plot of this object and its sinogram is shown in Fig. 12.17.”

Figure 12.17 does indeed contain a sinogram, but a very simple one: the sinogram of a point is just a sine wave. The reader is asked to produce a somewhat more complicated sinogram in homework Problem 29.

“Problem 29 An object consists of three $\delta$ functions at $(0, 2)$, $(\sqrt{3}, -1)$, and $(-\sqrt{3}, -1)$. Draw the sinogram of the object.”

This sinogram consists of three braided sine waves. I like this example, because it is simple enough that you the reader should be able to reason out the structure of the sinogram by imagining the projection in your head, but it is complicated enough that it is not trivial.

When preparing the 4th edition of Intermediate Physics for Medicine and Biology, I derived a couple new homework problems (Chapter 12, Problems 23 and 24) for which the inverse transformation can be solved analytically. I think these are useful exercises that build intuition with the Fourier Transform method of reconstructing an image (see Fig. 12.20, top path). It occurs to me now, however, that while these problems do provide insight and practice for the mathematically inclined reader, they also offer the opportunity to further illustrate the sinogram. So this week I made the figures below, showing the image $f(x,y)$ on the left and the corresponding sinogram $F(\theta, x')$ on the right, for the functions in Problems 23 and 24.
Let us try to interpret these pictures qualitatively. The vertical axis in the sinogram (right panel) indicates the angle, specifying the direction of the projection (the direction that the x-rays come from, to use CT terminology). The bottom of the $\theta$ axis is an angle of zero indicating x-rays are incident on the image from the bottom, the middle of the $\theta$ axis is x-rays incident from the left, and the top of the $\theta$ axis is x-rays incident from the top (see Fig. 12.12). Some authors extend the $\theta$ axis so it ranges from 0 to 360°, but to me that seems unnecessary since having the x-rays come from one side or the opposite side does not matter; it provides no new information. It is best if you, dear reader, pause now and stare at these sinograms until you understand how they relate to the image. If you really want to build your intuition, cover the left panel, and try to predict what the hidden image looks like from just the right panel. Or, solve homework Problems 30 and 31 in Chapter 12, and then plot both the image and its sinogram like I do above.

This website has some nice examples of sinograms. For instance, a sinogram of a line is just a point. Think about it and sketch some projections to convince yourself this is correct. Also this website shows a sinogram of a square located away from the center of the image (it looks like the sinogram above for Fig. 23, but with interesting bright curves tenuously weaving throughout the sinogram arising from the corners of the square). Finally, the website shows the sinogram of an
image known as a Shepp-Logan head phantom. (Warning, the website displays its sinograms rotated by 90° compared to the way Russ and I plot them; it plots the angle along the horizontal axis.) This video provides additional insight into the construction of the sinogram for the Shepp-Logan head phantom.

One of my favorite images is shown here; a detailed picture of a cross section of a torso, and its lovely sinogram. If you can do the inverse transformation of this complicated sinogram in your head, you’re a better medical physicist than I am.
Friday, January 25, 2013

**Aliasing**


“If a component [in the Fourier spectrum] is present whose frequency is more than half the sampling frequency, it will appear in the analysis at a lower frequency. This is the familiar stroboscopic effect in which the wheels of the stagecoach appear to rotate backward because the samples (movie frames) are not made rapidly enough. In signal analysis, this is called aliasing. It can be seen in Fig. 11.15, which shows a sine wave sampled at regularly spaced intervals that are longer than half a period.”

First of all, what is all this business about a stagecoach? Fifty years ago, when westerns were all the rage in movies and on TV, aliasing often occurred if the frame rate (typically 24 frames per second for old movies) was lower than the rotation rate of the wheel (if all the spokes of the wheel are equivalent, then you can take the “period of rotation” as the time it takes for one spoke to rotate to the position of the adjacent one, which may be much shorter than the time for the wheel to make one complete rotation). You can see an example of this in the John Wayne movie *Winds of the Wasteland* (1936), especially in the climactic scene of the stagecoach race. In this video clip from the movie, you can see aliasing of the stagecoach wheel briefly at times 3:04, 4:18, and 5:03. For those of you who are more discriminating in your movie tastes, you can see another example of aliasing 14 minutes and 21 seconds into *Stagecoach*, a John Wayne classic from 1939 directed by John Ford. In my opinion, the greatest western is the John Ford masterpiece *The Man Who Shot Liberty Valance*. What more could you ask for than both John Wayne and Jimmy Stewart in the same production? You can see aliasing briefly when Stewart drives his buckboard out of Shinbone to practice his pistol shooting (without much success). Another time when you see a wheel rotate backwards in this movie does not involve aliasing; it is (Spoiler Alert!) after Stewart Wayne kills Valance (Lee Marvin), when Pompey (Woody Strode) takes the drunken Wayne to his ranch house where he backs up the buckboard (that was a joke…).

But I digress. Aliasing can happen in space as well as time, and can therefore affect images. If spatial frequencies in the structure of an object correspond to wavelengths smaller than the twice the pixel size, low spatial frequency artifacts, such as Moire patterns, can appear in the image, shown nicely in this figure. One can minimize aliasing by first filtering (anti-aliasing) before sampling. Some rather extreme cases of aliasing can been seen in Figs. 11.41 and 12.11 of Intermediate Physics for Medicine and Biology.
When I arrived at graduate school, the main goal given to me by my advisor John Wikswo was to write scientific papers. Of course, I had to write a PhD dissertation, but that was in the distant future. The immediate job was to publish journal articles. John is a good writer, and he insists his students write well. So he recommended that I read the book Plain Words, by Sir Ernest Gowers. (I can’t recall if he made this suggestion before or after reading my first draft of a paper!) I dutifully read the book, which I have come to love. I believe I read the 1973 revision by Bruce Fraser although I am not sure; I borrowed Wikswo’s copy.

Gowers is an advocate for writing simply and clearly. He states in the introduction

“Here we come to the most important part of our subject. Correctness is not enough. The words used may all be words approved by the dictionary and used in their right senses; the grammar may be faultless and the idiom above reproach. Yet what is written may still fail to convey a ready and precise meaning to the reader. That it does so fail is the charge brought against much of what is written nowadays, including much of what is written by officials. In the first chapter I quoted a saying of Matthew Arnold that the secret of style was to have something to say and to say it as clearly as you can. The basic fault of present-day writing is a tendency to say what one has to say in as complicated a way as possible. Instead of being simple, terse and direct, it is stilted, long-winded and circumlocutory; instead of choosing the simple word it prefers the unusual.”

I have become a strong advocate for using plain language in scientific writing. Over the last three decades I have reviewed hundreds of papers for scientific journals, and I can attest that many scientists should read Plain Words. I have tried to use plain, clear language in the 4th edition of Intermediate Physics for Medicine and Biology (although Russ Hobbie’s writing was quite good in earlier editions of IPMB, which I had nothing to do with, so the book didn’t need much editing by me). Below, Gowers describes three rules for writing, which apply as well to scientific writing as to the official government writing that he focused on.

“What we are concerned with is not a quest for a literary style as an end in itself, but to study how best to convey our meaning without ambiguity and without giving unnecessary trouble to our readers. This being our aim, the essence of the advice of both these authorities [mentioned earlier] may be expressed in the following three rules, and the rest of what I have to say in the domain of the vocabulary will be little more than an elaboration of them.

- Use no more words than are necessary to express your meaning. For if you use more you are likely to obscure it and to tire your reader. In particular do not use superfluous adjectives and adverbs and do not use roundabout phrases where single words would serve.
- Use familiar words rather than the far-fetched, for the familiar are more likely to be readily understood.
- Use words with a precise meaning rather than those that are vague, for they will obviously serve better to make your meaning clear; and in particular prefer concrete words to abstract, for they are more likely to have a precise meaning.”
For me, the chore of writing is made easier because I like to write. Really, why else would I write this blog each week if I didn’t enjoy the craft of writing (certainly increased book sales can’t justify the time and effort). When my children were young, I once became secretary of their elementary school’s Parent-Teacher Association mainly because my primary duty would be writing the minutes of the PTA meetings. If you were to ask my graduate students, I think they would complain that I make too many changes to drafts of their papers, and we tend to go through too many iterations before submission to a journal. I can usually tell when we are close to a finished paper, because I find myself putting in commas in one draft, and then taking them out in the next. One trick Wikswo taught me is to read the text out loud, listening to the cadence and tone. I find this helpful, and I don’t care what people think when they walk by and hear me reading to myself in my office.

Most Americans have an advantage in the world of science. Modern science is primarily performed and published in the English language, which is our native tongue. I feel sorry for those who must submit articles written in an unfamiliar language—it really is unfair—but that has not stopped me from criticizing their English mercilessly in anonymous reviews. For any young scientist who may be reading this blog (and I do hope there are some of you out there), my advice is: learn to write. As a scientist, you will be judged on your written documents: your papers, your reports, and above all your grant proposals. You simply cannot afford to have these poorly written.

I believe role models are important in writing. One of mine is Isaac Asimov. While I enjoy his fiction, I use his science writing as an example of how to explain difficult concepts clearly. I was very lucky to have encountered his books when in high school. A second role model is not a science writer at all. I have read Winston Churchill’s books, especially his history of the second world war, and I find his writing both clear and elegant. A third model is physicist David Mermin. His textbook Solid State Physics is quite well written, and you can read his essay on writing physics here. You will find learning to write scientific papers difficult if all you read are other scientific papers, because the majority are not well written. If you pattern your own writing after them you will be aiming at the wrong target. Please, learn to write well.

You can read Plain Words online (and for free) here.

This week’s blog entry seems rather long and rambling. Let me conclude with a paraphrase of Mark Twain’s famous quip about letter writing: If I had more time, I would have written a shorter blog entry.
Musicophilia

Those who know me well are aware that I spend considerable time walking my dog Suki. Usually during these walks I am listening to recorded books. Being too cheap to spend money on this habit, I borrow these recordings from the Rochester Hills Public Library. They have an impressive selection, but Suki and I have been at this for a while (she is almost 11 years old), and I have slowly worked my way through their stock of recordings in genres that I ordinarily listen to; science, history, and biography. I don’t view this as a problem, because it has forced me to sample books about topics I would not ordinarily listen to. The most recent example is Musicophilia: Tales of Music and the Brain, by Oliver Sacks. Perhaps you object that this is actually a science book, but I view it more as a medical book outside my normal experience. Regardless, I was pleasantly surprised to find considerable medical physics discussed.

I had listened previously to Sacks’s delightfully-titled The Man Who Mistook His Wife for a Hat, so I knew what I was getting into. In Musicophilia, Sacks discusses a variety of abnormalities in the perception of music. For instance, he begins with musical hallucinations. This is more than just having a song stuck in your head. These were examples from his clinical practice of people who, say, suffered a brain injury and afterward would hear music in their mind that they could not distinguish from real music. They sometimes could not turn it on or off, but were stuck with it more or less continuously. Another example is people who, after a stroke, lost the ability to hear music as music. An opera sounds like someone screaming, and a symphony like pots and pans crashing onto the floor. In one case he related, this occurred to a former professional musician. It is amazing.

Sacks describes all sorts of brain studies being done to examine these patients. There is considerable discussion of data measured using electroencephalography, magnetoencephalography, positron emission tomography, functional magnetic resonance imaging, and transcranial magnetic stimulation—all of which Russ Hobbie and I analyze in the 4th edition of Intermediate Physics for Medicine and Biology. For me, hearing these stories makes me nostalgic for my years working at the National Institutes of Health, where I used to collaborate with neurologists such as Mark Hallett (whose research is mentioned by Sacks). Hallett and his team studied all sorts of odd diseases while I was helping them develop magnetic stimulation. In this case, we physicists and engineers were not discovering new biological ideas or medical abnormalities, but we were providing the tools for others to make these discoveries. And, oh, what tools!

Sacks notes there are some patients who have lost their ability to tell which of two tones is the higher pitch (but can still hum a song). These patients are in contrast with those rare individuals with perfect or absolute pitch; they can tell what note a sound is when heard in isolation. My sister has something approaching perfect pitch. When I was in high school, I took piano lessons. Whenever I played a wrong note while practicing (which was quite often) she would call out from an adjacent room “f-sharp!” or “b-flat!” Do you know how annoying it is not only to have your mistakes pointed out for all to hear, but also to have the specific note identified precisely? Worst of all, she was always right. Some of these piano pieces she had played herself, but others
she had not; she was just able to identify the pitch. I have always envied people with perfect pitch, but Sacks raises an interesting point. If people with perfect pitch hear a song played flawlessly but in the wrong key, they get all agitated and upset (he compared this to seeing a painting with all the colors wrong). I, on the other hand, would remain blissfully unaware of the problem. When I was in graduate school in Nashville, I bought a used piano from a blind fellow who refurbished pianos for a living. This particular piano was so old that he could not tighten its strings completely, so the piano was tuned about 3 steps too low (He gave me a good deal on it). The improper tuning never bothered me in the least. However, sometimes my weakness with tonal discrimination has caused me some embarrassment. I played tuba in my high school band, and before concerts the director would have us all “tune up”. The first clarinet would play a note, and we would each play the same note in turn to make sure we were in tune. I always hated this, because I could never tell if I was sharp or flat, and the director would usually end up yelling at me in frustration “You’re flat. Flat! Push the tuning slide in!”.

Sacks’s book got me to thinking about all sorts of unusual sensory perceptions. He describes people who could hear but could not perceive music, and I thought it must be like someone born without sight. But Sacks had a better analogy; imagine someone born colorblind (say, completely color blind, instead of just lacking one of three color receptors). How do you describe color to such a person? It has no meaning. How do you describe music to someone born unable to make sense of it? Then I began thinking of other odd sensory inputs, like magnetoreception and the ability to perceive the polarization of light. Humans can’t perceive these signals, but other species can. If you will let me indulge in a bit of anthropomorphization, I suspect there are some bird families who sit in their nest at night saying to each other “those humans can’t perceive magnetic fields or polarization! How to they ever get home?”

Finally, for those of you who know Suki, let me provide a quick update. Earlier this year she damaged her Anterior Cruciate Ligament, and our walks came to an abrupt halt. After much debate (she is a small dog, and is 10 years old) we decided to have her undergo surgery. The veterinary surgeon Dr. McAbee did a marvelous job, and we are now back to our walks as if nothing ever happened.
My Ideal Bookshelf

While browsing at the library recently, I ran across the book My Ideal Bookshelf, edited by Thessaly La Force, with artwork by Jane Mount. Their preface describes the book well.

“The assignment sounds straightforward enough. Select a small shelf of books that represent you—the books that have changed your life, that have made you who you are today, your favorite favorites. You begin, perhaps, by walking over to your bookshelf and skimming the spines on the top shelf. You pull down a handful that you remember loving; you grab a couple that you read over and over again. Some you know just by the color of their dust jackets. One is in tatters—it was passed down by your mother—and it’s dog-eared and carefully held together by tape and tenderness. The closer you look, the trickier the task turns out to be….

We asked more than one hundred creative people in a variety of disciplines from around the world to do exactly this. Chefs and architects, writers and fashion designers, filmmakers and ballet dancers all agreed to share their ideal bookshelves.”

It’s not the words that make this book is so interesting; it is the pictures. Each contributor had their bookshelf painted. The dust jackets says “Jane Mount’s original paintings of the colorful and delightful book spines and occasional objects d’art from the contributors’ personal bookshelves showcase the selections.” You can probably guess where this is going. I just had to collect the ideal bookshelf for the 4th edition of Intermediate Physics for Medicine and Biology. (Someone had too much time on his hands this week.) Here it is:

My illustration does not have the charm of Mount’s quirky paintings (see her create one of these illustrations here). I put mine together in powerpoint, and every book spine is a rectangle. If you like this sort of thing, browse through My Ideal Bookshelf and enjoy her enchanting artwork. If
you REALLY like My Ideal Bookshelf, you can pay big bucks and get prints of various book collections (see http://www.idealbookshelf.com).

How did I choose which books to include in my illustration? The book had to be cited in IPMB, it had to deal with either physics or the application of physics to biology, and I had to have access to a copy (either from my own office bookshelf or from the Oakland University library) so I could recall what the spine looked like. The towering blue volume of IPMB dominates the skyline that is my bookshelf. Some great authors are represented, including Edward Purcell, Philip Morrison, Art Winfree, Knut Schmidt-Nielsen, Leon Glass, and Howard Berg. Two volumes of the wonderful Berkeley Physics Course appear. Powers of Ten and The Machinery of Life are both beautifully illustrated, and would be the best choices from my shelf for mathophobes. I wanted to include Strogatz’s Nonlinear Dynamics and Chaos, but I couldn’t reproduce the marbled coloration of the spine using powerpoint.

Do you want to learn more about books related to IPMB? I listed my top ten books in an earlier blog entry, and a catalog of 40 books can be found in an Amazon.com Listmania! list for IPMB that I put together a while back. Click one button on that webpage and you can buy them all (I hope your credit card has a high limit).

Whose collection of books in My Ideal Bookshelf is closest to my taste? I resonated with the bookshelves of Atul Gawande (doctor and writer), John Maeda (graphic designer and computer scientist), and most of all Jonathan Zittrain (legal scholar and professor). For you voyeurs who want to peak further into my personal bookshelf, see another of my Listmania! lists containing my favorite books.
The Amazing World of Auger Electrons

When analyzing how ionizing radiation interacts with biological tissue, one important issue is the role of Auger electrons. In Intermediate Physics for Medicine and Biology, Russ Hobbie and I introduce Auger electrons in Chapter 15 (Interaction of Photons and Charged Particles with Matter). An x-ray or charged particle ionizes an atom, leaving a hole in the electron shell.

“The hole in the shell can be filled by two competing processes: a radiative transition, in which a photon is emitted as an electron falls into the hole from a higher level, or a nonradiative or radiationless transition, such as the emission of an Auger electron from a higher level as a second electron falls from a higher level to fill the hole.”

We consider Auger electrons again in Chapter 17 (Nuclear Physics and Nuclear Medicine). In some cases, a cascade of relatively low energy electrons is produced by one ionizing event.

“The Auger cascade means that several of these electrons are emitted per transition. If a radionuclide is in a compound that is bound to DNA, the effect of several electrons released in the same place is to cause as much damage per unit dose as high-LET [linear energy transfer] radiation….Many electrons (up to 25) can be emitted for one nuclear transformation, depending on the decay scheme [Howell (1992)]. The electron energies vary from a few eV to a few tens of keV. Corresponding electron ranges are from less than 1 nm to 15 μm. The diameter of the DNA double helix is about 2 nm…When it [the radionuclide emitting Auger electrons] is bound to the DNA, survival curves are much steeper, as with the α particles in Fig. 15.32 (RBE [relative biological effectiveness] ≈ 8)”

In IPMB, Russ and I cite a paper by Amin Kassis with the wonderful title “The Amazing World of Auger Electrons” (International Journal of Radiation Biology, 80: 789-803). Kassis begins

“In 1925, a 26-year-old French physicist named Pierre Victor Auger published a paper describing a new phenomenon that later became known as the Auger effect (Auger 1925). He reported that the irradiation of a cloud chamber with low-energy, X-ray photons results in the production of multiple electron tracts and concluded that this event is a consequence of the ejection of inner-shell electrons from the irradiated atoms, the creation of primary electron vacancies within these atoms, a complex series of vacancy cascades composed of both radiative and nonradiative transitions, and the ejection of very low-energy electrons from these atoms. In later studies, it was recognized that such low-energy electrons are also ejected by many radionuclides that decay by electron capture (EC) and/or internal conversion (IC). Both of these processes introduce primary vacancies in the inner electronic shells of the daughter atoms which are rapidly filled up by a cascade of electron transitions that move the vacancy towards the outermost shell. Each inner-shell electron transition results in the emission of either a characteristic atomic X-ray photon or low-energy and short-range monoenergetic electrons (collectively known as Auger electrons, in honor of their discoverer).

Typically an atom undergoing EC and/or IC emits several electrons with energies ranging from a few eV to approximately 100 keV. Consequently, the range of Auger electrons in
water is from a fraction of a nanometer to several hundreds of micrometers (table 1). The ejection of these electrons leaves the decaying atoms transiently with a high positive charge and leads to the deposition of highly localized energy around the decay site. The dissipation of the potential energy associated with the high positive charge and its neutralization may, in principle, also act concomitantly and be responsible for any observed biological effects. Finally, it is important to note that unlike energetic electrons, whose linear energy transfer (LET) is low (~0.2 keV/mm) along most of their rather long linear path (up to one cm in tissue), i.e. ionizations occur sparingly, the LET of Auger electrons rises dramatically to ~26 keV/mm (figure 1) especially at very low energies (35–550 eV) (Cole 1969) with the ionizations clustered within several cubic nanometers around the point of decay. From a radiobiological prospective, it is important to recall that the biological functions of mammalian cells depend on both the genomic sequences of double-stranded DNA and the proteins that form the nucleoprotein complex, i.e. chromatin, and to note that the organization of this polymer involves many structural level compactions (nucleosome, 30-nm chromatin fiber, chromonema fiber, etc.) [see Fig. 16.33 in IPMB] whose dimensions are all within the range of these high-LET (8–26 keV/mm), low-energy (less than 1.6 keV), short-range (less than 130 nm) electrons."

An example of an isotope that emits a cascade of Auger electrons is Iodine-125. It has a half-life of 59 days, and decays to an excited state of tellurium-125. The atom deexcites by various mechanism, including up to 21 Auger electrons with energies of 50 to 500 eV each. Kassis says

“Among all the radionuclides that decay by EC and/or IC, the Auger electron emitter investigated most extensively is iodine-125. Because these processes lead to the emission of electrons with very low energies, early studies examined the radiotoxicity of iodine-125 in mammalian cells when the radionuclide was incorporated into nuclear DNA consequent to in vitro incubations of mammalian cells with the thymidine analog 5-[^125]Ijodo-2'-deoxyuridine ([^125]IdUrd). These studies demonstrated that …[^125]I is highly toxic to mammalian cells.”

I like to compare ^125^I with ^131^I, another iodine radioisotope used in nuclear medicine. ^131^I undergoes beta decay, followed by emission of a gamma ray. Both the high energy electron from beta decay (up to 606 keV) and the gamma ray (364 keV) travel millimeters in tissue, passing through many cells. In contrast, ^125^I releases its cascade of Auger electrons, resulting in extensive damage over a very small distance. Civil War buffs might compare these two isotopes to the artillery ammunition of the 1860s. ^131^I is like a cannon firing shot (solid cannon balls), whereas ^125^I is like firing canister. If you are trying to take out an enemy battery 1000 yards away, you need shot. But if you are trying to repulse an enemy infantry charge that is only 10 yards away, you use canister or, better, double canister. ^131^I is shot, and ^125^I is double canister.
Physics of Phoxhounds

I don’t have any grandchildren yet, but I am fortunate to have a wonderful "granddog." This weekend, my wife and I are taking care of Auggie, the lovable foxhound that my daughter Kathy rescued from an animal shelter in Lansing, Michigan. Auggie gets along great with our Cocker-Westie mix, “Aunt Suki,” my dog-walking partner who I’ve mentioned often in this blog (here, here, here, and here).

Do dogs and physics mix? Absolutely! If you don’t believe me, then check out the website dogphysics.com. I plan to read How To Teach Physics To Your Dog with Auggie and Suki. In fact, according to this tee shirt foxhounds are particularly good at physics. Once we finish How To Teach Physics To Your Dog, we may move on to Physics for Dogs: A Crash Course in Catching Cats, Frisbees, and Cars. Apparently there is even a band that sings about dog physics, but I don’t know what that is all about.

Auggie is a big fan of the 4th edition of Intermediate Physics for Medicine and Biology. His favorite part is Section 7.10 (Electrical Stimulation) because there Russ Hobbie and I discuss the “dog-bone” shaped virtual cathode that arises when you stimulate cardiac tissue using a point electrode. He thinks “Auger electrons,” discussed in Sec. 17.11, are named after him. Auggie’s favorite scientist is Godfrey Hounsfield (Auggie adds a "d" to his name: “Houndsfield”), who earned a Nobel Prize for developing the first clinical computed tomography machine. And his favorite homework problem is Problem 34 in Chapter 2, about the Lotka-Volterra equations governing the population dynamics of rabbits and foxes.

How did Auggie get his name? I am not sure, because he had the name Auggie when Kathy adopted him. I suspect it comes from an old Hanna-Barbera cartoon about Augie Doggie and Doggie Daddy. When Auggie visits, I get to play doggie [grand]daddy, and say “Augie, my son, my son” in my best Jimmy Durante voice. I’m particularly fond of the Augie doggie theme song.


Our dog Suki has some big news this week. My friend and Oakland University colleague Barb Oakley has a new book out: A Mind for Numbers: How to Excel at Math and Science (Even if You Flunked Algebra). I contributed a small sidebar to the book offering some tips for learning physics, and it includes a picture of me with Suki! Thanks to my friend Yang Xia for taking the
picture. Barb is a fascinating character and author of an eclectic collection of books. I suggest Hair of the Dog: Tails from Aboard a Russian Trawler. Her amazon.com author page first gave me the idea of publishing a blog to go along with IPMB. To those of you who are interested in physics applied to medicine and biology but struggle with all the equations in IPMB, I suggest Barb's book or her MOOC Learning How to Learn.

James Herriot—the author of a series of wonderful books including All Creatures Great and Small, which will warm the heart of any dog-lover—loved beagles, which look similar to foxhounds, but are smaller. If you are looking for an uplifting and enjoyable book to read on a late-summer vacation (and you have already finished IPMB), try Herriot’s books. But skip the chapters about cats (yuck).

Auggie may not be the brightest puppie in the pack, and he is too timid to be an effective watch dog, but he has a sweet and loving disposition. I think of him as a gentle soul (even if he did chew up his grandma's shoe). Below is a picture of Auggie and his Aunt Suki, getting ready for their favorite activity: napping.
Friday, November 21, 2014

The MCAT and IPMB

The Medical College Admission Test, famously known as the MCAT, is an exam taken by students applying to medical school. The Association of American Medical Colleges will introduce a new version of the MCAT next year, focusing on competencies rather than on prerequisite classes. How well does the 4th edition of Intermediate Physics for Medicine and Biology prepare premed students for the MCAT?

The new MCAT will be divided into four sections, and the one most closely related to IPMB deals with the chemical and physical foundations of biological systems. Within that section are two foundational concepts, of which one is about how “complex living organisms transport materials, sense their environment, process signals, and respond to changes that can be understood in terms of physical principles.” This concept is further subdivided into five categories. Below, I review the topics included in these categories and indicate what chapter in IPMB addresses each.

**MCAT: Translational motion, forces, work, energy, and equilibrium in living systems**

IPMB: Chapter 1 discusses mechanics, including forces and torques, with applications to biomechanics. Work and energy are introduced in Chapter 1, and analyzed in more detail in Chapter 3 on statistical mechanics and thermodynamics (parts of thermodynamics are included under another foundational concept dealing mostly with chemistry). Periodic motion is covered in Chapter 11, which discusses the amplitude, frequency and phase of an oscillator. Waves are analyzed in Chapter 13 about sound and ultrasound.

**MCAT: Importance of fluids for the circulation of blood, gas movement, and gas exchange**

IPMB: Chapter 1 analyzes fluids, including buoyancy, hydrostatic pressure, viscosity, Poiseuille flow, turbulence, and the circulatory system. Much of this material is not covered in a typical introductory physics class. Chapter 3 introduces absolute temperature, the ideal gas law, heat capacity, and Boltzmann’s constant.

**MCAT: Electrochemistry and electrical circuits and their elements**

IPMB: Chapters 6 and 7 cover electrostatics, including charge, the electric field, current, voltage, Ohm’s law, resistors, capacitors, and nerve conduction. Chapter 8 discusses the magnetic field and magnetic forces.

**MCAT: How light and sound interact with matter**

IPMB: Sound is analyzed in Chapter 13, including the speed of sound, the decibel, attenuation, reflection, the Doppler effect, ultrasound, and the ear. Chapter 14 covers light, photon energy, color, interference, and the eye. This chapter also describes absorption of light in the infrared, visible, and ultraviolet. Chapter 18 analyzes nuclear magnetic resonance.
MCAT: Atoms, nuclear decay, electronic structure, and atomic chemical behavior

IPMB: Chapter 17 is about nuclear physics and nuclear medicine, covering isotopes, radioactive decay, and half-life. Atoms and atomic energy levels are explained in Chapter 14.

MCAT: General mathematical concepts and techniques

IPMB: Chapter 1 and many other chapters require students to estimate numerically. Chapter 2 covers linear, semilog, and log-log plots, and exponential growth. Metric units and dimensional analysis are used everywhere. Probability concepts are discussed in Chapter 3 and other chapters. Basic math skills such as exponentials, logarithms, scientific notation, trigonometry, and vectors are reinforced throughout the book and in the homework problems, and are reviewed in the Appendices.

The MCAT section about biological and biochemical foundations of living systems includes diffusion and osmosis (discussed in Chapters 4 and 5 of IPMB), membrane ion channels (covered in Chapter 9), and feedback regulation (analyzed in Chapter 10).

Overall, Intermediate Physics for Medicine and Biology covers many of the topics tested on the MCAT. A biological or medical physics class based on IPMB would prepare a student for the exam, and would reinforce problem solving skills and teach the physical principles underlying medicine, resulting in better physicians.

I am, however, a realist. I know premed students take lots of classes, and they don’t want to take more physics beyond a two-semester introduction, especially if the class might lower their grade point average. I have tried to recruit premed students into my Biological Physics (PHY 325) and Medical Physics (PHY 326) classes here at Oakland University, with little success. Perhaps if they realized how closely the topics and skills required for the MCAT correspond to those covered by IPMB they would reconsider.

To learn more about how to prepare for the physics competencies on the MCAT, see Robert Hilborn’s article Physics and the Revised Medical College Admission Test, published in the American Journal of Physics last summer (Volume 82, Pages 428-433, 2014).
On Writing Well

Oakland University, where I work, has an ADVANCE grant from the National Science Foundation, with the goal of increasing the representation and advancement of women in academic science and engineering careers. I am part of the leadership team for the Women in Science and Engineering at Oakland University (WISE@OU) Program, and one of my roles is to help mentor young faculty. Last Tuesday I led a WISE@OU workshop on Best Practices in Scientific Writing. The event was videotaped, and you can watch it here. I’m the bald guy who is standing and wearing the red shirt.

A list of writing resources was provided to all workshop participants (see below). It begins “For the most benefit in the least time with no cost, work through the Duke online Scientific Writing Resource, then read Part 1 (about 50 pages) of Zinsser’s book On Writing Well (available free online), and finally go through the online material for the Stanford Writing in the Sciences class.” If you don’t have enough time for even these three steps, then just read Zinsser, which is a delight.

Russ Hobbie and I try to write well in the 4th edition of Intermediate Physics for Medicine and Biology. You can decide if we succeed. Many readers of this blog are from outside the United States (I can tell from the "likes" on the book’s Facebook page). As I noted in the workshop, it is not fair that scientists from other countries must write science in a language other than their native tongue. Yet, most science is published in English, and scientists need to be able to write it well. So, my advice is to do whatever it takes to become a decent writer.

When I was in graduate school, my dissertation advisor John Wikswo gave me a copy of The Complete Plain Words, a wonderful book about writing originally published by Sir Ernest Gowers. Read it for free online. The version Wikswo loaned me was a later edition coauthored by Bruce Fraser. (You always should be concerned when a perfectly good book picks up a coauthor in later editions). This spring, Gowers’ great-granddaughter Rebecca Gowers is publishing a new edition of Plain Words. I can’t wait. Another oldie but goodie is Strunk and White’s The Elements of Style. The original, by William Strunk, is available online. (The second author of "Strunk and White" is E. B. White who wrote Charlotte’s Web; I vividly remember Mrs. Sheets reading Charlotte’s Web aloud to my third grade class at Northside Elementary School.) If you have time for only three words about writing, let them be Strunk’s admonition “omit needless words.”

I’ve come up with my own Three Laws of Writing Science, patterned after Isaac Asimov’s Three Laws of Robotics (regular readers of this blog know that Asimov influenced me greatly when I was in high school).

- First Law: What you write must be scientifically correct.
- Second Law: Write clearly, except when clarity would put you in conflict with the First Law.
- Third Law: Write concisely, except when conciseness would put you in conflict with the First or Second Laws.
Writing is easier when you enjoy doing it, and I always have. I once became secretary of the Parent-Teacher Association at my daughters’ elementary school because that job allowed me to write the minutes of the PTA meetings. If you don’t enjoy writing, take heart. You don’t need to be a great writer to succeed in science. Slipping into NSF-speak, if you can improve from “poor” or “fair” to “good” you will get almost the full benefit. Go from “good” to “very good” or “excellent” only if you like to write.

Best Practices in Scientific Writing

Below is a list of resources about scientific writing. For the most benefit in the least time with no cost, work through the Duke online Scientific Writing Resource, then read Part 1 (about 50 pages) of Zinsser’s book On Writing Well (available free online), and finally go through the online material for the Stanford Writing in the Sciences class.

Books about writing:

• Gowers R, Gowers E. 2014. Plain Words
• Gray-Grant D. 2008. 8½ Steps to Writing Better, Faster
• Pinker, S. 2014. The Sense of Style
• Silvia PJ. 2007. How to Write a Lot
• Strunk W, White EB. 1979. The Elements of Style
• Zinsser W. 1976. On Writing Well (free online: archive.org/details/OnWritingWell)

American Scientist article The Science of Scientific Writing

Video of Steven Pinker discussing good writing

A free online course from Stanford about Writing in the Sciences


How to Get Published. A discussion with Mike Sevilla and myself, moderated by George Corser, about writing and publishing scientific papers, hosted the OU graduate student group GradConnection.

A free online webinar debating the use of the active or passive voice

Duke University’s online Scientific Writing Resource, open to all.

Nonnative English speakers (and the rest of us too) should see the website Scientific English as a Foreign Language.
Friday, July 17, 2015

**Boston**

I did something unusual for me last evening: I went to a rock concert. As a birthday present, my daughter Stephanie took me to Freedom Hill Amphitheater to listen to the band **Boston**.

I was in high school in 1976 when I bought Boston’s famous debut album. That was a big year: it was the bicentennial of the United States, Jimmy Carter was elected president, Nadia Comaneci was earning 10s and then-Bruce Jenner won the decathlon in the Olympic games, much to my chagrin the Cincinnati Reds won the world series (but it wasn’t quite as exciting a series as the year before, which was the best world series ever), and the Apple Computer Company was formed by Steve Jobs and Steve Wozniak. My family moved from Fort Wayne, Indiana to Ashland, Ohio, and I spent the year playing tuba in the high school band, managing the high school baseball team, reading my first Isaac Asimov book, wondering if I should study physics in college, and listening to Chicago, the Eagles, Peter Frampton, the Wings, and Boston. The severe winter of 1976-1977 in northern Ohio and the simultaneous energy crisis resulted in my high school missing several weeks of classes, so some of my friends and I had time to establish our own garage band: "Hades." We didn’t have a singer, and my role was to pick out the melody on an electric keyboard while the guitars and drums banged out behind me. Only a few years later disco music and the Bee Gees drove me from rock to country music, which I have listened to ever since.

My ears are still tingling a bit from the concert. How loud was it? Chapter 13 in the 5th edition of *Intermediate Physics for Medicine and Biology* discusses the decibel scale for measuring sound intensity, a logarithmic scale defined as \( \log_{10}(I/I_o) \), where \( I \) in the sound intensity and the reference \( I_o \) is the minimum perceptible sound \( (10^{-12} \text{ W m}^{-2}) \). Table 13.1 says 120 dB is the threshold for pain, and 130 dB is typical for the peak sound at a rock concert. Stephanie and I were sitting in the back of the amphitheater, so I doubt we ever experienced 130 dB, but we were up there pretty high on the decibel scale. I probably didn’t lose any hair cells in my cochlea (see Section 13.5), but I wonder how the band plays concerts night after night without suffering hearing loss. As people age, they tend to lose the ability to hear high tones: presbycusis. I may not have heard the music last night in the same way I heard it in 1976; some of those frequencies may be lost to me forever.

The leader of Boston is **Tom Scholz**, their 68-year-old guitar player and keyboardist. Scholz was educated as a mechanical engineer, and might be one of the few rock musicians who would enjoy reading IPMB. I found that I could identify with Scholz in some respects: he is past his prime, no longer topping the charts or breaking new ground in rock and roll. But, after decades in the business, he is still out there performing, playing his music, and even sometimes writing new songs. It makes me want to go write another paper!
The Psychic Probe

In the summer my wife and I sometimes take long car trips, and I often listen to audiobooks while I drive to keep me awake and alert. During a recent trip I listened to Isaac Asimov’s Foundation trilogy. Regular readers of this blog know that I am a huge Asimov fan. I first read the Foundation series about forty years ago, and this was my third or fourth time through these delightful books.

In brief, the Foundation series tells the history of the decaying galactic empire, and describes the work of the psychohistorian Hari Seldon who has calculated mathematically how to reduce the duration of the dark ages following the empire’s fall from 30,000 years to merely 1000. All goes according to plan until the Mule, a mutant who can control other people’s emotions, causes all to go awry.

One of Asimov’s inventions in this future history is a device that can read minds, called the Psychic Probe. He writes in Foundation and Empire,

“‘The general threw away his shredded, never-lit cigarette, lit another, and shrugged. ‘Well, it is beside the immediate point, this lack of first-class tech-men. Except that I might have made more progress with my prisoner were my Psychic Probe in proper order.’

The secretary's eyebrows lifted. 'You have a Probe?'

‘An old one. A superannuated one which fails me the one time I needed it. I set it up during the prisoner's sleep, and received nothing. So much for the Probe. I have tried it on my own men and the reaction is quite proper, but again there is not one among my staff of tech-men who can tell me why it fails upon the prisoner. Ducem Barr, who is a theoretician of parts, though no mechanic, says the psychic structure of the prisoner may be unaffected by the Probe since from childhood he has been subjected to alien environments and neural stimuli. I don't know. But he may yet be useful. I save him in that hope.’ ”

Of course, Russ Hobbie and I don’t mention the Psychic Probe in the 5th edition of Intermediate Physics for Medicine and Biology….or do we? Asimov didn’t explain the physical mechanism behind the Probe, but I can speculate. Four candidates are:

- **Magnetoecephalography.** The probe could be a form of MEG, as discussed in Section 8.5 of IPMB. The probe would then contain a sensitive magnetic field detector, like modern SQUID magnetometers, that could record brain activity whether we wanted it to or not.
- **Functional Magnetic Resonance Imaging.** Section 18.12 of IPMB describes how fMRI can use magnetic field heterogeneities caused by oxygenated hemoglobin to detect brain activity. Essentially, one measures blood flow, which is related to neural firing.
- **Positron Emission Tomography.** PET images the distribution of injected positron emitters (Section 17.10 of IPMB). For example, the isotope fluorine-18 can be attached to
molecules of glucoses, which are then taken up by parts of the brain that are metabolically active and become trapped inside neurons.

- **Transcranial Magnetic Stimulation.** In Section 8.7 of IPMB, Russ and I discuss using a rapidly changing magnetic field to excite nerve axons. TMS can disrupt brain function, and has even been suggested as a treatment for depression.

PET and fMRI are too slow to accurately follow rapid brain activity. PET detects brain metabolism and fMRI detects blood flow, both of which are only indirectly related to neuron firing. My best guess for the Psychic Probe is some combination of MEG and TMS. Apparently the probe can damage the brain when used aggressively, which suggests TMS. But it can also read minds when used more gently, which points toward MEG. A combo TMS/MEG unit could therefore both detect and alter brain function.

While working at NIH in the 1990s, I studied both magnetoencephalography and transcranial magnetic stimulation. Yikes! I may be partially responsible for the invention of the Psychic Probe!
Learning Biology

Suppose you are a physicist, mathematician, or engineer who wants to change your research direction toward biology and medicine. How do you learn biology? Let’s assume you don’t quit your day job, so you have limited time. Here are my suggestions.

1. Read *The Machinery of Life* (2nd edition), by David Goodsell. I discussed this book a few weeks ago in this blog. It is visual, easy to read, not too long, cheap, and doesn’t get bogged down in details. It’s a great introduction; this is where I would start.

2. If you haven’t had an introductory biology class, you might consider taking this online biology class from MIT. It is free, it has homework assignments and quizzes so you can assess your learning, and you can work at your own schedule. For those who prefer an online class to reading a book, this is the thing to do.

3. If you would prefer reading an introductory biology textbook, a popular one is *Campbell Biology* by Reece et al., now in its 10th edition. The MIT online course mentioned above and the introductory biology classes here at Oakland University use this book. Its advantages are that it covers all of biology and it is written for introductory students. Its disadvantages are that it is expensive and long. I am not an expert on the different introductory biology textbooks; there may be others just as good.

4. I like to learn a subject by studying its history. If you want to try this, I suggest: *The Double Helix* by James Watson (of Watson and Crick) and *The Eighth Day of Creation* by Horace Freeland Judson. Watson’s book is a classic: a first-person account the discovery of the structure of DNA. It is well written, controversial, and should be read by anyone interested in science. The Eighth Day of Creation is longer and more comprehensive, but it is a fantastic book.

5. The textbook *Physical Biology of the Cell* by Phillips et al. was written by physicists trying to learn biology. Also from a physicist’s point of view are *Biological Physics* and *Physical Models of Living Systems*, both by Philip Nelson. These books do not cover all of biology, but a physicist may like them.

6. I learned a lot of biology in high school reading Isaac Asimov books. They often take a historical approach, and are qualitative, interesting, clearly written, fairly short, and cheap. I worry about recommending them because biology has progressed so much over the last few decades that these books from the 1960s are out-of-date. However, I suspect they are still useful introductions, and I suggest *The Wellsprings of Life*, *The Genetic Code*, *The Human Body*, *The Human Brain*, and *A Short History of Biology*.

7. Some books from my ideal bookshelf cover parts of biology from the point of view of a physicist: *Air and Water* by Mark Denny, *Scaling: Why is Animal Size so Important?* by Knut Schmidt-Nielsen, and *Random Walks in Biology* by Howard Berg. Steven Vogel has many books you might like, including *Life in Moving Fluids*, *Vital Circuits*, and *Life’s Devices*.

9. Once you have a general biology background, what comes next? When I was in graduate school, I sat in on the Vanderbilt Medical School’s Physiology class and their Biochemistry class. These are the two courses that I encourage Oakland University Medical Physics graduate students to take. Typical textbooks are Guyton and Hall’s Textbook of Medical Physiology, now in its 13th edition, and Nelson and Cox's Lehninger Principles of Biochemistry, now in its 6th edition. Both books are long, expensive, and detailed. If interested in cell and molecular biology, a leading text is Molecular Biology of the Cell by Bruce Alberts and Alexander Johnson.

10. If you have the time, you can do what Russ Hobbie did: between 1971 and 1973 he audited all the courses medical students take in their first two years at the University of Minnesota. Finally, you can always purchase a copy of the 5th edition of Intermediate Physics for Medicine and Biology!

If readers of the blog have their own recommendations, please add them in the comments.
The Magnetic Field of a Single Axon (Part 1)

**The Magnetic Field of a Single Axon**
A Comparison of Theory and Experiment

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**Abstract**
The magnetic field and the transmembrane action potential of a single nerve axon were measured simultaneously. The volume conductor model was used to calculate the magnetic field from the measured action potential, allowing comparison of the model predictions with the experimental data. After analyzing the experiment for all systematic errors, we conclude that the shape of the magnetic field can be accurately predicted from the transmembrane potential and, more importantly, the shape of the transmembrane potential can be calculated from the magnetic field. This allows for the internal resistance of the axon, to be \( r_i = 1.9 \times 10^{-4} \) mm \(^{-1}\), implying a value for the internal conductivity of \( \sigma_i = 0.33 \Omega^{-1} \) m \(^{-1}\). Magnetic measurements are compared with standard biocoelectrical techniques for studying nerve axons.

Thirty years ago, John Wikswo and I published *The Magnetic Field of a Single Axon: A Comparison of Theory and Experiment* (Biophysical Journal, Volume 48, Pages 93-109, 1985). This was my second journal article (and my first as first author). Russ Hobbie and I cite it in Chapter 8 of the 5th edition of *Intermediate Physics for Medicine and Biology*. I reproduce the introduction below.

“An active nerve axon can be modeled with sufficient accuracy to allow a detailed calculation of the associated magnetic field. Therefore the single axon provides a simple, yet fundamentally important system from which we can test our understanding of the relation between biomagnetic and bioelectric fields. The magnetic field produced by a propagating action potential has been calculated from the transmembrane action potential using the volume conductor model (1). The purpose of this paper is to verify that calculation experimentally. To make an accurate comparison between theory and experiment, we must be careful to correct for all systematic errors present in the data.

To test the volume conductor model it is necessary to measure the transmembrane potential and magnetic field simultaneously. An experiment performed by Wikswo et al. (2) provided preliminary data from a lobster axon, however the electric and magnetic signals were recorded at different positions along the axon and no quantitative comparisons were made between theory and experiment. In the experiment reported here, these limitations were overcome and improved instrumentation was used (3-5).”

As the introduction notes, the volume conductor model was described in reference (1) by Jim Woosley, Wikswo and myself (*The Magnetic Field of a Single Axon: A Volume Conductor Model*, Mathematical Biosciences, Volume 76, Pages 1-36, 1985). I discussed the calculation of the magnetic field previously in this blog, so today I restrict myself to the experiment.

I was not the first to measure the magnetic field of a single axon. Wikswo’s student, J. C. Palmer, had made preliminary measurements using a lobster axon; reference (2) is to their earlier paper. One of the first tasks Wikswo gave me as a new graduate student was to reproduce and improve Palmer’s experiment, which meant I had to learn how to dissect and isolate a nerve. Lobsters were too expensive for me to practice with so I first dissected cheaper crayfish nerves; our plan was that once I had gotten good at crayfish we would switch to the larger lobster. I
eventually became skilled enough in working with the crayfish nerve, and the data we obtained was good enough, that we never bothered with the lobsters.

I recorded the transmembrane potential using a glass microelectrode. The electrode is made starting with a hollow glass tube, about 1 mm in diameter. We had a commercial microelectrode puller, but it was an old design and had poor control over timing. So, one of my jobs was to design the timing circuitry (see here for more details). The glass would be warmed by a small wire heating element (much like you have in a toaster, but smaller), and once the glass was soft the machine would pull the two ends of the tube apart. The hot glass stretched and eventually broke, providing two glass tubes with long, tapering tips with a hole at the narrow end of about 1 micron diameter. I would then backfill these tubes with 2 Molar potassium citrate. The concentration was so high that when I occasionally forgot to clean up after an experiment I would come back the next day and find the water had evaporated leaving impressive, large crystals. The back end of the glass tube would be put into a plexiglass holder that connected the conducting fluid to a silver-chloride electrode, and then to an amplifier.

One limitation of these measurements was the capacitance between the microelectrode and the perfusing bath. Because the magnetic measurements required that the nerve be completely immersed in saline, I could not reduce the stray capacitance by lowering the height of the bath. This capacitance severely reduced the rate of rise of the action potential, and to correct for it we used “negative capacitance”. We applied a square voltage pulse to the bath, and measured the microelectrode signal. We then adjusted the frequency compensation knob on the amplifier (basically, a differentiator) until the resulting microelectrode signal was a square pulse. That was the setting we used for measuring the action potential. Whenever I changed the position of the electrode or the depth of the bath, I had to recalibrate the negative capacitance.

To record the transmembrane potential, I would poke the axon (easy to see under a dissecting microscope) with a microelectrode. Often the tip of the electrode would not enter the axon, so I would tap on the lab bench creating a vibration that was just sufficient to drive the electrode through the membrane. Usually I had the output of the microelectrode amplifier go to a device that output current with a frequency that varied with the microelectrode voltage. I would put this current through a speaker, so I could listen for when the microelectrode tip was successfully inside the axon because the DC potential would drop by about 70 mV (the axon’s resting potential) and therefore the pitch of the speaker would suddenly drop.

Next week I will continue this story, describing how we measured the magnetic field.
The Magnetic Field of a Single Axon (Part 2)

In my last blog entry, I began the story behind The Magnetic Field of a Single Axon: A Comparison of Theory and Experiment (Biophysical Journal, Volume 48, Pages 93-109, 1985). I wrote this paper as a graduate student working for John Wikswo at Vanderbilt University. (I use the first person “I” in this blog post because I was usually alone in a windowless basement lab when doing the experiment, but of course Wikswo taught me how to do everything including how to write a scientific paper.) Last week I described how I measured the transmembrane potential of a crayfish axon, and this week I explain how I measured its magnetic field.

The magnetic field was recorded using a wire-wound toroid (I have talked about winding toroids previously in this blog). Wikswo had obtained several ferrite toroidal cores of various sizes, most a few millimeters in diameter. I wound 50 to 100 turns of 40-gauge magnet wire onto the core using a dissecting microscope and a clever device designed by Wikswo to rotate the core around several axes while holding its location fixed. I had to be careful because a kink in a wire having a diameter of less than 0.1 mm would break it. Many times after successfully winding, say, 30 turns the wire would snap and I would have to start over. After finishing the winding, I would carefully solder the ends of the wire to a coaxial cable and “pot” the whole thing in epoxy. Wikswo—who excels at building widgets of all kinds—had designed Teflon molds to guide the epoxy. I would machine the Teflon to the size we needed using a mill in the student shop. (With all the concerns about liability and lawsuits these days student shops are now uncommon, but I found it enjoyable, educational, and essential.) Next I would carefully place the wire-wound core in the mold with a Teflon tube down its center to prevent the epoxy from sealing the hole in the middle. This entire mold/core/wire/cable would then be placed under vacuum (to prevent bubbles), and filled with epoxy. Once the epoxy hardened and I removed the mold, I had a “toroid”: an instrument for detecting action currents in a nerve. In 1984, this "neuromagnetic current probe" earned Wikswo an IR-100 award. The basics of this measurement are described in...
In Wikswo’s original experiment to measure the magnetic field of a frog sciatic nerve (the entire nerve; not just a single axon), the toroid signal was recorded using a SQUID magnetometer (see Wikswo, Barach, Freeman, Magnetic Field of a Nerve Impulse: First Measurements. Science, 208:53-55, 1980). By the time I arrived at Vanderbilt, Wikswo and his collaborators had developed a low-noise, low-input impedance amplifier—basically a current-to-voltage converter—that was sensitive enough to record the magnetic signal (Wikswo, Samson, Giffard, A Low-Noisy Low Input Impedance Amplifier for Magnetic Measurements of Nerve Action Currents, IEEE Trans. Biomed. Eng. 30:215-221, 1983). Pat Henry, then an instrument specialist in the lab, ran a cottage industry building and improving these amplifiers.

To calibrate the instrument, I threaded the toroid with a single turn of wire connected to a current source that output a square pulse of known amplitude and duration (typically 1 μA and 1 ms). The toroid response was not square because we sensed the rate-of-change of the magnetic field (Faraday’s law), and because of the resistor-inductor time constant of the toroid. Therefore, we had to adjust the signal using “frequency compensation”; integrating the signal until it had the correct square shape.

The amplifier output was recorded by a digital oscilloscope that saved the data to a tape drive. Another of my first jobs at Vanderbilt was to write a computer program that would read the data from the tape and convert it to a format that we could use for signal analysis. We wrote our own signal processing program—called OSCOPE, somewhat analogous to MATLAB—that we used to analyze and plot the data. I spent many hours writing subroutines (in FORTRAN) for OSCOPE so we could calculate the magnetic field from the transmembrane potential, and vice versa.

Once all the instrumentation was ready, the experiment itself was straightforward. I would dissect the ventral nerve cord from a crayfish and place it in a plexiglass bath (again, machined in the student shop) filled with saline (or more correctly, a version of saline for the crayfish called Van Harreveld’s solution). The nerve was gently threaded through the toroid, a microelectrode was poked into the axon, and an electrode to record the extracellular potential was placed nearby. I would then stimulate the end of the nerve. It was easy to excite just a single
axon; the nerve cord split to go around the esophagus, so I could place the stimulating electrode there and stimulate either the left or right half. In addition, the threshold of the giant axon was lower than that of the many small axons, so I could adjust the stimulator strength to get just one giant axon.

When I first started doing these experiments, I had a horrible time stimulating the nerve. I assumed I was either crushing or stretching it during the dissection, or there was something wrong with the saline solution, or the epoxy was toxic. But after weeks of checking every possible problem, I discovered that the coaxial cable leading to the stimulating electrode was broken! The experiment had been ready to go all along; I just wasn’t stimulating the nerve. Frankly, I now believe it was a blessing to have a stupid little problem early in the experiment that forced me to check every step of the process, eliminating many potential sources of trouble and giving me a deeper understanding of all the details.

As you can tell, a lot of effort went into this experiment. Many things could, and did, go wrong. But the work was successful in the end, and the paper describing it remains one of my favorites. I learned much doing this experiment, but probably the most important thing I learned was perseverance.
The Mystery of the Flawed Homework Problem

When teaching PHY 325 (Biological Physics) this fall, I assigned my students homework from the 5th edition of Intermediate Physics for Medicine and Biology. One problem comes from Section 7.10 about Electrical Stimulation.

Problem 36. If the medium has a constant resistance, find the energy required for stimulation as a function of pulse duration.

The odd thing is, when I looked in the solution manual to review how to solve this problem, it contained answers to parts (a) and (b), and (b) is the most useful part. Where are (a) and (b)? Somehow when preparing the 5th edition, part (b) was left out (it’s missing from the 4th edition too). Nevertheless, part (b) ended up in the solution manual (don’t ask me how). This is what Problem 36 should look like:

Problem 36. The longevity of a pacemaker battery is related to the energy required for stimulation.

(a) Find an expression for the energy $U$ expended by a pacemaker to stimulate the heart as a function of the pulse duration $t$. Use the Lapicque strength-duration curve (Eq. 7.45), and assume the body and electrodes have a constant resistance $R$. Sketch a plot of energy versus duration.

(b) In general you want to stimulate using the least energy. Determine what duration minimizes the energy expended per pulse.

I don’t usually solve homework problems from the book in this blog, but because the interesting part of this problem was left out of IPMB I don’t think it will hurt in this case. Also, it provides readers with a sneak peak at the solution manual. Remember that Russ Hobbie and I will only send the solution manual to instructors, not students. So if you are teaching from IPMB and want the solution manual, by all means contact us. If you are a student, however, you had better talk to your instructor.

7.36 Issues such as pacemaker battery life are related to the energy required for electrical stimulation. This problem relates the energy to the strength-duration curve, and provides additional insight into the physical significance of the chronaxie.

(a) Let the resistance seen by the electrode due to the medium be $R$. The power is $i^2R$. Therefore the total energy is

$$U = i^2 R t = R t^2 \left( 1 + \frac{t_c}{t} \right)^2 t$$

(b) The duration corresponding to minimum energy is found by setting $dU/dt = 0$. We get
\[ 0 = \left(1 + \frac{t_C}{t}\right)^2 - 2\left(1 + \frac{t_C}{t}\right)\frac{t_C}{t} \]

which reduces to \( t = t_C \). The minimum energy corresponds to a duration equal to the chronaxie.

In the 5th edition’s solution manual, each problem has a brief preamble (in italics) explaining the topic and describing what the student is supposed to learn. We also mark problems that are higher difficulty (*), that complete a derivation from the text (§), and that are new in the fifth edition (¶). Problem 7.36 didn’t fall into any of these categories. We typically outline the solution, but don’t always show all the intermediate steps. I hope we include enough of the solution that the reader or instructor can easily fill in anything missing.

One thing not in the solution manual is the plot of energy, \( U \), versus duration, \( t \). Below I include such a plot. The energy depends on the rheobase current \( i_R \), the chronaxie \( t_C \), and the resistance \( R \).

I wonder if this change to Problem 7.36 should go into the IPMB errata? It is not really an error, but more of an omission. After some thought, I have decided to include it, since it was supposed to be there originally. You can find the errata at the book’s website: www.oakland.edu/~roth/hobbie.htm. I urge you to download it and mark the corrections in your copy of IPMB.

I hope this blog post has cleared up the mystery behind Problem 7.36. Yet, the curious reader may have one last question: why did I assign a homework problem to my students that is obviously flawed? The truth is, I chose which homework problems to assign by browsing through the solution manual rather than the book (yes, the solution manual is that useful). Problem 7.36 sure looked like a good one based on the solution manual!
Star Wars

With *The Force Awakens* opening in theaters, now is the perfect time to answer your questions about how *Intermediate Physics for Medicine and Biology* relates to *Star Wars*. (Warning: This post is spoiler laden for Episodes I - VI, but not for Episode VII which I haven't seen yet.)

1. With so many light saber duels, why is there so little blood? Even blasters kill without gore or carnage. In Section 14.11 of IPMB, Russ Hobbie and I discuss tissue ablation. According to Wookieepedia, ablation cauterizes wounds, preventing bleeding. This is the same reason we use lasers in surgery.

2. Why do blaster shots not propagate at the speed of light? Chapter 14 of IPMB gives the speed of light as $3 \times 10^8$ m/s. In Star Wars, shots travel not much faster than a hard-thrown fastball, maybe 100 m/s. Apparently this far-away galaxy has a large permeability of free space, $\mu_0$. Next time you view these films, watch for exaggerated magnetic effects.

3. How did Han Solo freeze so quickly (and reversibly!) in carbonite? The bioheat equation developed in Chapter 14 of IPMB implies that heat diffuses into tissue, and over long distances diffusion is slow. My guess is that carbonite freezing makes use of the blood flow term in the bioheat equation, perhaps by rapidly injecting cold carbonite intravenously. However, I don’t see any IV tubes coming out of Han. Do you? Carbonite freezing has to be dangerous. But no matter; had Han died during freezing, Chewbacca would have saved Princess Leia.

4. How does Luke Skywalker’s artificial hand work? Chapter 7 of IPMB discusses electrical stimulation of nerves, which is crucial for developing neural prostheses. Luke had such a prosthesis after he lost his hand during his epic duel with Darth Vader (Luke's FATHER!). Functional neural stimulation is becoming so sophisticated that artificial hands may arrive sooner than you think.

5. How does Darth Vader control his breathing? Chapter 10 in IPMB analyzes feedback loops, and our main example describes how we control the carbon dioxide in our blood by adjusting our ventilation rate. I wonder, does Vader’s mask break that feedback loop? Perhaps a carbon dioxide sensor in the mask adjusts the rate of his slow, heavy breathing. I suspect something is horribly wrong with his physiological control mechanism, because once the mask comes off Vader dies.

6. What determines the anatomy of all those alien life forms? In Chapter 2 of IPMB, Russ and I describe how size impacts the structure of animals: scaling. One famous result involves the strength of bones. Body mass scales as length cubed, but the strength of a bone scales as its radius squared, meaning that bones must get thicker relative to their length in larger animals. This is why Jabba the Hutt has no legs. Yoda lied when he said “size matters not.”

7. How did Luke avoid freezing to death on Hoth? When an animal dies, it loses heat according to Newton’s Law of Cooling (Chapter 3 in IPMB). After Han killed the tauntaun and shoved
Luke into its belly, its temperature began to fall exponentially. Luke must have gotten really cold. What saved him was immersion into a bacta tank, which speeds rewarming by taking advantage of convection as well as conduction. I suspect bacta may also contain suspended stem cells, but who knows? Whatever the mechanism, Luke survived. During his recuperation is the most disturbing event in the entire Star Wars saga: the incestuous kiss. Ewwwwww!

8. What did leaders of the Rebel Alliance say when they realized that Vader knew about their plans to attack the Death Star? One way to measure radiation dose is to use thermoluminescent phosphors, which Russ and I describe in Chapter 16 of IPMB as a “dielectric material that has been doped with impurities or has missing atoms in the crystal lattice to form metastable energy levels or traps.” So, Admiral Ackbar must have just discovered the mechanism of thermoluminescence when he exclaimed “It’s a trap!”

If you want answers to all of your Star Wars questions, keep a copy of Intermediate Physics for Medicine and Biology handy. Before watching the new film, find time for a Star Wars marathon (with episodes in machete order, thereby avoiding Jar Jar Binks). Finally, don’t miss my favorite version of the Star Wars theme song, performed in the video below by lounge singer Nick Winters. Now, off to the movies. And, May The Force Be With You.
The Rest of the Story

Alan was born 102 years ago today in Banbury, England. He was descended from a long line of Quakers. Quakers are often pacifists, so Alan’s dad George didn’t fight in World War I. Instead, he took part in a relief effort in the Middle East. But war is dangerous even if you are not in the line of fire, and George died of dysentery in Baghdad when Alan was only four.

Alan’s mom was left to raise him and his two brothers alone. She encouraged Alan’s interest in science, and so did his eccentric Aunt Katie who took him bird watching. When he was 15, Alan was hired by an ornithologist to survey rookeries and heronries. He spent hours searching for rare birds in salt marshes. All this kindled his passion for learning.

Based on his strong academic record, Alan won a scholarship to study botany, zoology, and chemistry at Trinity College, part of the University of Cambridge. One of Cambridge’s distinguished zoologists gave Alan some good advice: study as much physics and mathematics as you can! So he did. He also did what all undergraduates should do: research. He was good at it; so good that he was awarded a Rockefeller Fellowship to go to New York for a year. He kept at his research, and traveled around to other parts of the United States, such as Massachusetts and Saint Louis, to learn more.

When he got back to Cambridge, Alan’s knowledge of physics allowed him to build his own equipment, enabling him to move his research in exciting directions. He and his collaborators began to get dramatic results. Just when he was on the verge of making decisive discoveries, Hitler marched into Poland and the world was at war again.

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Alan suspended his own research and dedicated his talents to defeating the Germans. The Battle of Britain was won, in part, by the development of radar. Alan worked on a special type of radar that was installed in airplanes and used by RAF fighter pilots to locate and intercept Luftwaffe bombers. Alan and a small group of scientists toiled frantically, working seven days a week. They risked their lives on test flights in planes fitted with the new radar. For six years, during what should have been a young scientist’s most productive period, Alan set aside his own interests to help the Allies win the war.

Once World War II ended, Alan returned to Cambridge. After all this time, had science passed him by? No! He took up his research where he had left off, and started making groundbreaking discoveries in electrophysiology. With his coworkers, Alan figured out how nerves send signals down their axons, first passing sodium ions through the cell membrane and then passing potassium ions.

In 1963, Alan Hodgkin received the 1963 Noble Prize for Physiology or Medicine for discovering the ionic mechanism of nerve excitation.
And now you know THE REST OF THE STORY. Good day!

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This blog post was written in the style of Paul Harvey’s wonderful “The Rest of the Story” radio program. The content is based on Hodgkin’s autobiography Chance and Design: Reminiscences of Science in Peace and War. You can read about Hodgkin’s work on electrophysiology—including Hodgkin and Huxley’s famous mathematical model of the nerve action potential—in Chapter 6 of Intermediate Physics for Medicine and Biology.

Happy birthday, Alan Hodgkin!
Friday, April 1, 2016

Strat-O-Matic Baseball

Monday is opening day!

When I was young I was an avid baseball fan. I still enjoy the game, but now I haven’t time to follow it closely. My childhood team was the Chicago Cubs. I can still remember the lineup: shortstop Don Kessinger led off, second baseman Glenn Beckert hit next, left fielder Billy Williams batted third, and third baseman Ron Santo was cleanup. Ferguson Jenkins was the pitching ace, colorful Joe Pepitone—a former Yankee—arrived by trade to play first, Mr. Cub Ernie Banks was in the twilight of his career, and hot-tempered Leo Durocher was the manager. The Miracle Mets broke my heart in 1969, when the Cubs led their division into September only to collapse in the season’s final weeks. The Cubs have not won the World Series since 1908, but I still love ’em. Maybe this year?

I wasn’t a good little league player; I struck out a lot, and I was assigned to play right field, where I could do the least damage with my glove. Yet, I had fun. One summer when I was in junior high, because of the timing of the age cutoffs and my birthday, I was nearly the oldest player in my age group. That was my best summer, when I approached mediocrity. I enjoyed the sport so much that I volunteered to manage the high school team. For those not familiar with baseball, being the manager in high school is very different than managing a professional team. In high school, the manager washes the uniforms, keeps track of the equipment, collects player statistics, and—my favorite job—draws the foul lines on the field before each game.

When growing up in Morrison, Illinois, my friend Ted Paul owned the game Strat-O-Matic Baseball. It was played with dice and player cards, allowing you to recreate baseball games from your armchair. Unfortunately, Strat-O-Matic Baseball was expensive. We were not poor, but the price was out of the range my parents spent on birthday or Christmas presents. Necessity is the mother of invention, so I reverse engineered the game, making my own cards and rules that mimicked Strat-O-Matic’s in some ways but in other ways were my own creation.

In order to do make my version of Strat-O-Matic Baseball, I had to learn the basics of probability. I didn’t need advanced concepts, and you can find all the necessary probability theory in Chapter 3 of Intermediate Physics for Medicine and Biology. Two ideas are key. First, the probability that one or the other of two mutually exclusive events happens is found by adding their individual probabilities. For instance, the probability of rolling either a one, two, or three on a single die is equal to the probability of rolling a one plus the probability of rolling a two plus the probability of rolling a three. Second, the probability that two independent events both happen is found by multiplying their individual probabilities. For example, the probability of throwing a one on the first die and a three on the second is equal to the probability of throwing a one plus the probability of throwing a two plus the probability of throwing a three. This concept underlies the joint probability distribution described in Appendix M of IPMB. These two rules, plus some counting, is all the math required to recreate Strat-O-Matic baseball. I also needed a source of baseball statistics, supplied by Street and Smith’s Baseball Yearbook, published each year around Valentine’s Day and well within the family gift budget. In retrospect, making my own version of Strat-O-Matic
Baseball was not difficult, but for a twelve-year-old kid I think I did a pretty good job.

Let me explain briefly how Strat-O-Matic Baseball works. The game was based on batters’ cards and pitchers’ cards. First you roll one die, and if you get a 1, 2, or 3 you use the batter’s card; a 4, 5, or 6 means you use the pitcher's card. Then you roll two dice which determine the outcome of the at-bat: out, walk, single, double, triple, or home run. The trick is to match the player’s statistics to the probability of a particular throw of the dice. The pitchers’ cards were hardest to create, because Street and Smith didn’t tabulate batting averages given up by pitchers, so I had to invent an algorithm based on wins, earned run average, and strikeouts. I remember spending many hours playing my homemade Strat-O-Matic baseball. In some ways it was pathetic: a child playing alone in his room with just his dice and cards. But in other ways it was romantic: thrilling late night ballgames with all the drama and excitement of sports, but performed just for me.

Even now, when I teach probability I focus on those key concepts I used when creating my version of Strat-O-Matic Baseball. Sometimes you learn more when you play than when you work.
Trivial Pursuit IPMB

Trivial Pursuit is a popular and fun board game invented in the 1980s. While playing it, you learn many obscure facts (trivial, really).

When my daughter Kathy was in high school, she would sometimes test out of a subject by studying over the summer and then taking an exam. Occasionally I would help her study by skimming through her textbook and creating Trivial Pursuit-like questions. We would then play Trivial Pursuit using my questions instead of those from the game. I don't know if it helped her learn, but she always passed those exams.

Readers of Intermediate Physics for Medicine and Biology may want a similar study aid to help them learn about biological and medical physics. Now they have it! At the book website you can download 100 game cards for Trivial Pursuit: IPMB. To play, you will need the game board, game pieces, and instructions of the original Trivial Pursuit, but you replace the game cards by the ones I wrote.

In case you have never played, here are the rules in a nutshell. The board has a circle with spots of six colors. You roll a die and move your game piece around the circle, landing on the spots. Your opponent asks you a question about a topic determined by the color. If you answer correctly you roll again; if you are wrong your opponent rolls. There are special larger spots where a correct answer gets you a little colored wedge. The first person to get all six colored wedges wins.

The original version of Trivial Pursuit had topics such as sports or literature. The Trivial Pursuit: IPMB topics are

- Numbers and Units (blue)
- People (pink)
- Anatomy and Physiology (yellow)
- Biological Physics (brown)
- Medical Physics (green)
- Mathematics (orange).

One challenge of an interdisciplinary subject like medical and biological physics is that you need a broad range of knowledge. I suspect mathematicians will find the math questions to be simple, but the biologists may find them difficult. Physicists may be unfamiliar with anatomy and physiology, and chemists may find all the topics hard. The beauty of the game is that it rewards a broad knowledge across disciplines.

Many may find the People section most challenging. I suggest you only require the player to know the person's last name, although the first name is also given on my game card. In Units and Numbers I generally only require numbers to be known approximately. The goal is to have an order-of-magnitude knowledge of biological parameters and physical constants. Many questions
ask you to estimate the size of an object, like in Section 1.1 of IPMB. For the math and physics questions you may need a pencil and paper handy, because some of the questions contain equations. You can't simply show your opponent the equation on the game card, because both the questions and answers are together. This is unlike the real Trivial Pursuit game cards, which had the answers on the back. Unfortunately, such two-sided cards are difficult to make.

I know the game is not perfect. Some questions are truly trivial and others ask for some esoteric fact that no one would be expected to remember. Some questions may have multiple answers of which only one is on the card. You can either print out the game cards (requiring 100 pieces of paper) or use a laptop or mobile device to view the pdf. I try to avoid repetitions, but with 100 game cards some may have slipped in inadvertently.

I may try using Trivial Pursuit: IPMB next time I teach Biological Physics (PHY 325) or Medical Physics (PHY 326) here at Oakland University. It would be excellent for, say, the last day of class, or perhaps a day when I know many students will be absent (such as the Wednesday before Thanksgiving). It does not teach important high-level skills, such as learning to use mathematical models to describe biology, or understanding how physics constrains the way organisms evolve. You cannot teach a complex and beautiful subject like tomography using Trivial Pursuit. But for learning a bunch of facts, the game is useful.

Enjoy!
Five Generations

When my first daughter Stephanie was born, we included her in this photo of five generations. From left to right are my maternal grandmother, my great-grandmother (born 1889), my daughter Stephanie (born 1988), me, and my mom. My great grandmother lived to be over 100 years old. I remember playing poker with her when I was young; she generally won and kept the money!

Recently I took another five-generation photo. There now exist five generations (editions) of Intermediate Physics for Medicine and Biology. My office is one of the few places you can find all five on one bookshelf. I was co-author on the fourth and fifth editions; the first three editions were authored by Russ Hobbie alone.

I have a special fondness for the first edition, which I bought for a class taught by my PhD advisor John Wikswo at Vanderbilt University in the early 1980s (price: $31.95). That is where I learned much of my biological and medical physics. When Russ was preparing the second edition, he asked John and I to create some 3D figures of the electrical potential and magnetic field of a nerve axon. There figures have appeared in each subsequent edition and are Figs. 7.13 and 8.14 in the fifth. My third edition is pretty beat up. It is the textbook I taught out of for several years after I arrived at Oakland University. The fourth and fifth editions I know best, as I helped write them (although Russ remains the primary force behind every edition).

The book has changed over the years. The first seven chapters are the same in all versions, but Russ added chapters on charged membranes and biomagnetism in the second edition. The first edition's chapter on signal analysis split into two in the second: one on 1D signal analysis and another on 2D images. The 4th edition picked up a chapter on ultrasound. The first edition's chapter on x-rays fissioned into a chapter on how x-rays interact with tissue and a chapter on the medical uses of x-rays. Finally, the second edition introduced a chapter on magnetic resonance imaging. Early editions featured a figure on the cover. I particularly like the first edition's electrocardiogram picture (Fig. 7.16 in the 5th edition). Russ and I planned on using a computed tomography illustration, Fig. 12.12, on the 4th edition cover, but Springer opted to use a generic cover with no figure.
Working on revisions of IPMB has been a pleasure and an honor. But really, the five generations of IPMB is a tribute to Russ Hobbie and his vision of advancing the teaching of physics in medicine and biology, which he has pursued over nearly four decades. I hope you find the book as useful as I have.
An Analytical Example of Filtered Back Projection

One of my hobbies is to find tomography problems that can be solved analytically. I know this is artificial—all tomography for medical imaging uses numerical computation—but as a learning tool analytical analysis helps build insight. I have some nice analytical examples using the Fourier method to solve the tomography problem (see homework problems 26 and 27 in chapter 12 of Intermediate Physics for Medicine and Biology), but I don't have a complete analytical example to illustrate the filtered back projection method (see a previous post for a partial example). Russ Hobbie and I do include a numerical example in section 12.6 of IPMB. I have always wondered if I can do that example analytically. Guess what: I can! Well, almost.

Start with a top-hat function for your object

\[ f(x, y) = \begin{cases} 
1, & x^2 + y^2 < a^2 \\
0, & \text{otherwise} 
\end{cases} \]

If we set \( x = 0 \), we can plot it as function of \( y \)

The projection of this function is given in IPMB; homework problem 36 asks the reader to derive it

\[ F(\theta, x') = \begin{cases} 
2\sqrt{a^2 - x'^2}, & |x'| < a \\
0, & |x'| > a 
\end{cases} \]

Because the object looks the same from all directions, the projection is independent of the angle. Below is a plot of the projection as a function of \( x' \). It is identical to the top panel of IPMB's Figure 12.22.
The next step is to filter the projection, which means we have to take its Fourier transform, multiply the transform by a high-pass filter, and then do the inverse Fourier transform. The Fourier transform of the projection is

\[ C(\theta, k) = \int_{-\infty}^{\infty} F(\theta, x') \cos(kx') \, dx' = 4 \int_{0}^{a} \sqrt{a^2 - x'^2} \cos(kx') \, dx' \]

This integral is not trivial, but Abramowitz and Stegun’s Handbook of Mathematical Functions With Formulas, Graphs and Mathematical Tables contains (page 360, equation 9.1.20)

\[ \int_{0}^{a} \sqrt{a^2 - x'^2} \cos(kx') \, dx' = \frac{\pi a}{2|k|} J_1(|k|a) \]

where \( J_1 \) is a first-order Bessel function (see homework problem 10). Because the projection is an even function, the sine part of the Fourier transform vanishes.

Filtering is easy; multiply by \(|k|/2\pi\). The result is

\[ C_\gamma(\theta, k) = a J_1(|k|a) \]

To find the inverse Fourier transform, we need

\[ G(\theta, x') = \frac{1}{2\pi} \int C_\gamma(\theta, k) \cos(kx') \, dk = \frac{a}{\pi} \int J_1(ka) \cos(kx') \, dk \]

This integral appears in Abramowitz and Stegun (page 487, equation 11.4.37)

\[ \int_{0}^{\infty} J_1(ka) \cos(kx') \, dk = \begin{cases} \frac{\cos(\sin^{-1}(x/a))}{\sqrt{a^2 - x'^2}} & |x'| < a \\ -\frac{a}{\sqrt{x'^2 - a^2} (|x'| + \sqrt{x'^2 - a^2})} & |x'| > a \end{cases} \]

After some simplification (which I leave to you), the filtered projection becomes

\[ G(\theta, x') = \begin{cases} 1 & |x'| < a \\ \frac{1}{\sqrt{(x'/a)^2 - 1 (|x'| + \sqrt{(x'/a)^2 - 1})}} & |x'| > a \end{cases} \]

Below is a plot of the filtered projection, which you should compare to the middle panel of Fig. 12.22. It looks the same as the plot in IPMB, except in the numerical calculation there is some ringing near the discontinuity that is not present in the analytical solution.
The final step is back projection. Because the projection is independent of the angle, we can calculate the back projection along any radial line, such as along the y axis

\[ f_b(0, y) = \int_0^{\pi} G(\theta, y \sin \theta) d\theta \]

If \( |y| \) is less than \( a \), the back projection is easy: you just get 1. Thus, the filtered back projection is the same as the object, as it should be. If \( |y| \) is greater than \( a \), the result should be zero. This is where I get stuck; I cannot do the integral. If any reader can solve this integral (and presumably show that it gives zero), I would greatly appreciate hearing about it. Below is a plot of the result; the part in red is what I have not proven yet. Compare this plot to the bottom panel of Fig. 12.22.

What happens if you do the back projection without filtering? You end up with a blurry image of the object. Guess what: I can solve this case analytically too! For \( |y| \) less than \( a \), the back projection without filtering is

\[ f_b(0, y) = \int_0^{\pi} F(\theta, x) d\theta = 4a \int_0^{\pi/2} \sqrt{1 - \left(\frac{y}{a}\right)^2 \sin^2 \theta} d\theta \]

which is \( 4a \) times the complete elliptic integral of the second kind

\[ E(\kappa) = \int_0^{\pi/2} \sqrt{1 - \kappa^2 \sin^2 \theta} d\theta \]

For \( |y| \) greater than \( a \), you get the more complicated expression

\[ f_b(0, y) = \int_0^{\pi} F(\theta, x) d\theta = 4a \int_0^{\sin^{-1}(a/y)} \sqrt{1 - \left(\frac{y}{a}\right)^2 \sin^2 \theta} d\theta \]

which is the incomplete elliptic integral of the second kind.
\[ E(\kappa, \phi) = \int_{0}^{\phi} \sqrt{1 - \kappa^2 \sin^2 \theta} \, d\theta \]

The trickiest part of the calculation is determining the upper limit on the integral, which arises because for some angles the projection is zero (you run into the same situation in homework problem 35, which I highly recommend). Readers who are on the ball may worry that the elliptic integral is tabulated only for \( \kappa < 1 \), but there are ways around this (see Abramowitz and Stegun, page 593, equation 17.4.16). When I plot the result, I get

which looks like Fig. 12.23 in IPMB.

So, now you have an analytical example that illustrates the entire process of filtered back projection. It even shows what happens if you forget to filter before back projecting. For people like me, the Bessel functions and elliptic integrals in this calculation are a source of joy and beauty. I know that for others they may be less appealing. To each his own.

I will rely on you readers to fill in the one missing step: show that the filtered back projection is zero outside the top hat.
PHY 325 and PHY 326

One reason I write this blog is to help instructors who adopt Intermediate Physics for Medicine and Biology as their textbook. I teach classes from IPMB myself; here at Oakland University we have a Biological Physics class (PHY 325) and a Medical Physics class (PHY 326). Instructors might benefit from seeing how I structure these classes, so below are my most recent syllabi.

### Syllabus, Biological Physics
**Fall 2015**

Class: Physics 325, MWF, 8:00-9:07, 378 MSC

Instructor: Brad Roth, Dept. Physics, 166 Hannah Hall, 370-4871, roth@oakland.edu, fax: 370-3408, office hours MWF, 9:15-10:00, [https://files.oakland.edu/users/roth/web](https://files.oakland.edu/users/roth/web)

Text: Intermediate Physics for Medicine and Biology, 5th Edition, by Hobbie and Roth (An electronic version of this book is available for free through the OU library)

Book Website: [https://files.oakland.edu/users/roth/web/hobbie.htm](https://files.oakland.edu/users/roth/web/hobbie.htm) (get the errata!).

Book Blog: [http://hobbieroth.blogspot.com](http://hobbieroth.blogspot.com)

Goal: To understand how physics influences and constrains biology

**Grades**

<table>
<thead>
<tr>
<th>Grade Type</th>
<th>Weight %</th>
<th>Exam Date</th>
<th>Chapters</th>
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<td>Point/Counterpoint</td>
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<tr>
<td>Exam 1</td>
<td>20</td>
<td>Feb 5</td>
<td>Chapters 1-3</td>
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<td>Exam 2</td>
<td>20</td>
<td>March 18</td>
<td>Chapters 4-6</td>
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<td>Exam 3</td>
<td>20</td>
<td>April 20</td>
<td>Chapter 7, 8, 10</td>
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<td>Comprehensive</td>
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<tr>
<td>Homework</td>
<td>25</td>
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**Schedule**

- Sept 4: Introduction
- Sept 9, 11: Chapter 1 Mechanics, Fluid Dynamics
- Sept 14-18: Chapter 2 Exponential, Scaling
- Sept 21-25: Chapter 3 Thermodynamics
- Sept 28-Oct 2: Exam 1
- Oct 5-9: Chapter 4 Diffusion
- Oct 12-16: Chapter 5 Osmotic Pressure
- Oct 19-23: Chapter 6 Electricity and Nerves
Oct 26-30  Exam 2
Nov 2-6  Chapter 7  Extracellular Potentials
Nov 9-13  Chapter 8  Biomagnetism
Nov 16-20  Chapter 10  Heart Arrhythmias, Chaos
Nov 23, 25  Chapter 10  Feedback
Nov 30-Dec 4  Chapter 10  Feedback
Dec 7  Review
Dec 9  Final Exam

Homework

Chapter 1:  6, 7, 8, 16, 17, 33, 40, 42  due Wed, Sept 16
Chapter 2:  3, 5, 10, 29, 42, 46, 47, 48  due Wed, Sept 23
Chapter 3:  29, 30, 32, 33, 34, 40, 47, 48  due Wed, Sept 30
Chapter 4:  7, 8, 12, 20, 22, 23, 24, 41  due Wed, Oct 14
Chapter 5:  1, 3, 5, 6, 7, 8, 10, 16  due Wed, Oct 21
Chapter 6:  1, 2, 22, 28, 37, 41, 43, 61  due Wed, Oct 28
Chapter 7:  1, 10, 15, 24, 25, 36, 42, 47  due Wed, Nov 11
Chapter 8:  3, 10, 24, 25, 27, 28, 29, 32  due Wed, Nov 18
Chapter 10:  12, 16, 17, 18, 40, 41, 42, 43  due Wed, Dec 2

Syllabus, Medical Physics
Winter 2016

Class: Physics 326, MWF, 10:40-11:47, 204 DH

Instructor: Brad Roth, Department of Physics, 166 HHS, (248) 370-4871, roth@oakland.edu, fax: (248) 370-3408, office hours MWF 9:30-10:30, https://files.oakland.edu/users/roth/web.


Book Website: https://files.oakland.edu/users/roth/web/hobbie.htm (get the errata!).

Book Blog: http://hobbieroth.blogspot.com

Goal: To understand how physics contributes to medicine

Grades

Point/Counterpoint  5 %
Exam 1  Feb 5  20 % Chapters 13-15
Exam 2  March 18  20 %  Chapters 16, 11-12  
Exam 3  April 20  20 %  Chapter 17, 18  
Final Exam  April 20  10 %  
Homework  25 %  

Schedule  
Jan 6, 8  Introduction  
Jan 11, 13, 15  Chpt 13  Sound and Ultrasound  
Jan 20, 22  Chpt 14  Atoms and Light  
Jan 25, 27, 29  Chpt 15  Interaction of Photons and Matter  
Feb 1, 3, 5  Exam 1  
Feb 8, 10, 12  Chpt 16  Medical Uses of X rays  
Feb 15, 17, 19  Chpt 11  Least Squares and Signal Analysis  
Feb 22, 24, 26  Winter Recess  
Feb 29, March 2, 4  Chpt 12  Images  
March 7, 9, 11  Chpt 12  Images  
March 14, 16, 18  Exam 2  
March 21, 23, 25  Chpt 17  Nuclear Medicine  
March 28, 30, Apr 1  Chpt 17  Nuclear Medicine  
April 4, 6, 8  Chpt 18  Magnetic Resonance Imaging  
April 11, 13, 15  Chpt 18  Magnetic Resonance Imaging  
April 18  Conclusion  
April 20  Final Exam  

Homework  
Chapter 13:  7, 10, 12, 21, 22, 27, 30, 36  due Fri, Jan 22  
Chapter 14:  4, 5, 16, 21, 22, 47, 48, 49  due Wed, Jan 27  
Chapter 15:  2, 4, 5, 10, 12, 14, 15, 16  due Wed, Feb 3  
Chapter 16:  4, 5, 7, 16, 19, 20, 22, 31  due Wed, Feb 17  
Chapter 11:  9, 11, 15, 20, 21, 36, 37, 41  due Wed, Mar 2  
Chapter 12:  7, 9, 10, 23  due Wed, Mar 9  
Chapter 12:  25, 32, 34, 35, and 27 (extra credit)  due Wed, Mar 16  
Chapter 17:  1, 2, 7, 9, 14, 17, 20, 22  due Wed, Mar 30  
Chapter 17:  29, 30, 40, 54, 57, 58, 59, 60  due Wed, Apr 6  
Chapter 18:  9, 10, 13, 14, 15, 18, 35, 49  due Wed, Apr 13  

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Point/Counterpoint articles

Jan 8: The 2014 initiative is not only unnecessary but it constitutes a threat to the future of medical physics. Med Phys, 38:5267-5269, 2011.


Jan 29: The more important heavy charged particle radiotherapy of the future is more likely to be with heavy ions rather than protons. Med Phys, 40:090601, 2013.


March 4: Recent data show that mammographic screening of asymptomatic women is effective and essential. Med Phys, 39:4047-4050, 2012.

March 11: PDT is better than alternative therapies such as brachytherapy, electron beams, or low-energy x rays for the treatment of skin cancers. Med Phys, 38:1133-1135, 2011.


April 1: Within the next ten years treatment planning will become fully automated without the need for human intervention. Med Phys, 41:120601, 2014.

April 8: Medical use of all high activity sources should be eliminated for security concerns. Med Phys, 42:6773, 2015.

April 15: MRI/CT is the future of radiotherapy treatment planning. Med Phys, 41:110601, 2014.

Notes:

- The OU library has an electronic version of IPMB that students can download. If they are willing to read pdfs, they have no textbook expense in either class.
- I skip Chapter 9. I have nothing against it. There just isn't time for everything.
- I cover Chapters 13-16 before the highly mathematical Chapters 11-12. I don't like to start the semester with a week or two of math.
• In Medical Physics, we spend the last 15 minutes of class each Friday discussing a point/counterpoint article from the Journal *Medical Physics*. The students seem to really enjoy this.
• I let the students work together on the homework, but they cannot simply copy someone else's work. They must turn in their own assignment.
• Both PHY 325 and PHY 326 are aimed at upper-level undergraduates. The prerequisites are a year of introductory physics and a year of introductory calculus. The students tend to be physics majors, medical physics majors, bioengineering majors, plus a few biology, chemistry, math, and mechanical engineering majors. The typical enrollment is about ten.
• I encourage premed students to take these classes. Occasionally one does, but not too often. I wish more would, because I believe it provides an excellent preparation for the MCAT. Unfortunately, they have little room in their busy schedule for two extra physics classes.
• OU offers a medical physics major. It consists of many traditional physics classes, these two specialty classes (PHY 325 and PHY 326), plus some introductory and intermediate biology.
• I am a morning person, so I often teach at 8 am. The students hate it, but I love it. Sometimes, however, I cannot control the time of day for the class and I teach at a later time.
Word Clouds

I have always wondered about those funny-looking collections of different-sized, different-colored words: the word cloud. This week I learned how to create a word cloud from any text I choose using the free online software at www.wordclouds.com. Of course, I chose Intermediate Physics for Medicine and Biology. Here is what I got:

The word cloud speaks for itself, but let me add a few comments. First, I deleted the preface, the table of contents, and the index from a pdf copy of IPMB before submitting it. The software was having trouble with such a large input file, and reducing the size seemed to help. After the list of words and their frequencies was created, I edited it. The software is smart enough to not include common words like "the" and "is", but I deleted others that seemed generic to me, like "consider" and "therefore." I kept words that appeared at least 250 times, which was about 65 words. The most common word was "Fig", as in "...spherical air sacs called alveoli (Fig. 1.1b)." The third most common was "Problem" as in "Problem 1. Estimate the number of....". I considered removing these, but illustrations and end-of-chapter exercises are an important part of the book, so they stayed. I was surprised by the second most common word: "energy". Russ Hobbie and I did not set out to make this a unifying theme in the book, but apparently it is.

I will let you decide if this word cloud is profound or silly. It was fun, and I like to share fun things with the readers of IPMB. Enjoy!
Whiplash

Last week, my wife Shirley and I were in an automobile accident. We suffered no serious injuries, thank you, but the car was totaled and we were sore for several days. After the obligatory reflections on the meaning of life, I began to think critically about the biomechanics of auto accident injuries.

Our car was at a complete stop, and the idiot in the other car hit us from behind. The driver’s side air bag deployed and the impact pushed us off to the right of the road (we hit the car in front of us in the process), while the idiot’s car ended up on the opposite shoulder. The police came and our poor car was carried off on a wrecker to a junk yard. Shirley and I walked home; the accident occurred about a quarter mile from our house.

My neck is still stiff. Presumably I suffered a classic—but not too severe—whiplash. Although Intermediate Physics for Medicine and Biology does not discuss whiplash, it does cover most of the concepts needed to understand it: acceleration, shear forces, torques, and biomechanics. Paul Davidovits describes whiplash briefly in Physics in Biology and Medicine. From the second edition:

“5.7 Whiplash Injury

Neck bones are rather delicate and can be fractured by even a moderate force. Fortunately the neck muscles are relatively strong and are capable of absorbing a considerable amount of energy. If, however, the impact is sudden, as in a rear-end collision, the body is accelerated in the forward direction by the back of the seat, and the unsupported neck is then suddenly yanked back at full speed. Here the muscles do not respond fast enough and all the energy is absorbed by the neck bones, causing the well-known whiplash injury.”

You can learn more about the physics of whiplash in the paper “Kinematics of a Head-Neck Model Simulating Whiplash” published in The Physics Teacher (Volume 46, Pages 88-91, 2008).

“In a typical rear-end collision, the vehicle accelerates forward when struck and the torso is pushed forward by the seat. The structural response of the cervical spine is dependent upon the acceleration-time pulse applied to the thoracic spine and interaction of the head and spinal components. During the initial phases of the impact, it is obvious that the lower cervical vertebrae move horizontally faster than the upper ones. The shear force is transmitted from the lower cervical vertebrae to the upper ones through soft tissues between adjacent vertebrae one level at a time. This shearing motion contributes to the initial development of an S-shape curvature of the neck (the upper cervical spine undergoes flexion while the lower part undergoes extension), which progresses to a C-shape curvature. At the end of the loading phase, the entire head-neck complex is under the extension mode with a single curvature. This implies the stretching of the anterior and compression of the posterior parts of the cervical spine.”

Here are links to videos showing what happens to the upper spine during whiplash:
Injury from whiplash depends on the acceleration. What sort of acceleration did my head undergo? I don’t know the speed of the idiot’s car, but I will guess it was 25 miles per hour, which is equal to about 11 meters per second. Most of the literature I have read suggests that the acceleration resulting from such impacts occurs in about a tenth of a second. Acceleration is change in speed divided by change in time (see Appendix B in IPMB), so \((11 \text{ m/s})/(0.1 \text{ s}) = 110 \text{ m/s}^2\), which is about 11 times the acceleration of gravity, or 11 \(g\). Yikes! Honestly, I don’t know the idiot’s speed. He may have been slowing down before he hit me, but I don’t recall any skidding noises just before impact.

What lesson do I take from this close call with death? My hero Isaac Asimov—who wrote over 500 books in his life—was asked what he would do if told he had only six months to live. His answer was “type faster.” Sounds like good advice to me!
Noninvasive Deep Brain Stimulation via Temporally Interfering Electric Fields

A fascinating paper, titled Noninvasive Deep Brain Stimulation via Temporally Interfering Electric Fields, was published in the June 1 issue of Cell (Volume 169, Pages 1029-1041) by Nir Grossman and his colleagues. Although I don’t agree with everything the authors say (I never do), on the whole this study is an important contribution. You may have seen Pam Belluck’s article about it in the New York Times. Below is Grossman et al.'s abstract.

“We report a noninvasive strategy for electrically stimulating neurons at depth. By delivering to the brain multiple electric fields at frequencies too high to recruit neural firing, but which differ by a frequency within the dynamic range of neural firing, we can electrically stimulate neurons throughout a region where interference between the multiple fields results in a prominent electric field envelope modulated at the difference frequency. We validated this temporal interference (TI) concept via modeling and physics experiments, and verified that neurons in the living mouse brain could follow the electric field envelope. We demonstrate the utility of TI stimulation by stimulating neurons in the hippocampus of living mice without recruiting neurons of the overlying cortex. Finally, we show that by altering the currents delivered to a set of immobile electrodes, we can steerablely evoke different motor patterns in living mice.”

The gist of the method is to apply two electric fields to the brain, one with frequency $f_1$ and the other with frequency $f_2$, where $f_2 = f_1 + \Delta f$ with $\Delta f$ small. The result is a carrier with a frequency equal to the average of $f_1$ and $f_2$, modulated by a beat frequency equal to $\Delta f$. For instance, the study uses two currents having frequencies $f_1 = 2000$ Hz and $f_2 = 2010$ Hz, resulting in a carrier frequency of 2005 Hz and a beat frequency of 10 Hz. When they use this current to stimulate a mouse brain, the mouse neurons respond at a frequency of 10 Hz.

The paper uses some fancy language, like the neuron “demodulating” the stimulus and responding to the “temporal interference”. I think there is a simpler explanation. The authors show that in general a nerve does not respond to a stimulus at a frequency of 2000 Hz, except that when this stimulus is first turned on there is a transient excitation. I would describe their beat-frequency stimulus as like the turning on and off of a 2000 Hz current. Each time the stimulus turns on (every 100 ms) you get a transient response. This gives you a neural response at 10 Hz, as observed in the experiment. In other words, a sinusoidally modulated carrier doesn’t act so differently from a carrier turned on and off at the same rate (modulated by a square wave), as shown in the picture below. The transient response is the key to understanding its action.
Stimulating neurons at the beat frequency is an amazing result. Why didn’t I think of that? Just as astonishing is the ability to selectively stimulate neurons deep in the brain. We used to worry about this a lot when I worked on magnetic stimulation at the National Institutes of Health, and we concluded that it was impossible. The argument was that the electric field obeys Laplace’s equation (the wave equation under conditions when propagation effects are negligible so you can ignore the time derivatives), and a solution to Laplace’s equation cannot have a local maximum. But the argument doesn’t seem to hold when you stimulate using two different frequencies. The reason is that a weak single-frequency field doesn’t excite neurons (the field strength is below threshold) and a strong single-frequency field doesn’t excite neurons (the stimulus is so large and rapid that the neuron is always refractory). You need two fields of about the same strength but slightly different frequencies to get the on/off behavior that causes the transient excitation. I see no reason why you can’t get such excitation to occur selectively at depth, as the authors suggest. Wow! Again, why didn’t I think of that?

I find it interesting to analyze how the electric field behaves. Suppose you have two electric fields, one at frequency $f_1$ that oscillates back-and-forth along a direction down and to the left, and another at frequency $f_2$ that oscillates back-and-forth along a direction down and to the right (see the figure below). When the two electric fields are in phase, their horizontal components cancel and their vertical components add, so the result is a vertically oscillating electric field (vertical polarization). When the two electric fields are 180 degrees out of phase, their vertical components cancel and their horizontal components add, so the result is a horizontally oscillating electric field (horizontal polarization). At times when the two electric fields are 90 degrees out of phase, the electric field is rotating (circular polarization). Therefore, the electric field's amplitude doesn't change much but its polarization modulates with the beat frequency. If stimulating an axon for which only the electric field component along its length is important for excitation, you project the modulated circular polarization onto the axon direction and get the beat-frequency electric field as discussed in the paper. It’s almost like optics. (OK, maybe “temporal interference” isn’t such a bad phrase after all.)
A good paper raises as many question as it answers. For instance, how exactly does a nerve respond to a beat-frequency electric field? I would like to see a computer simulation of this case based on a neural excitation model, such as the Hodgkin-Huxley model. (You can learn more about the Hodgkin-Huxley model in Chapter 6 of Intermediate Physics for Medicine and Biology; you knew I was going to get a plug for the book in here somewhere.) Also, unlike long straight axons in the peripheral nervous system, neurons in the brain bend and branch so different neurons may respond to electric fields in different (or all) directions. How does such a neuron respond to a circularly polarized electric field?

When I first read the paper’s final sentence—“We anticipate that [the method of beat-frequency stimulation] might rapidly be deployable into human clinical trials, as well as studies of the human brain”—I was skeptical. Now that I’ve thought about it more, I willing to…ahem…not dismiss this claim out-of-hand. It might work. Maybe. There is still the issue of getting a current applied to the scalp into the brain through the high-resistance skull, which is why transcranial magnetic stimulation is more common than transcranial electric stimulation for clinical applications. I don’t know if this new method will ultimately work, but Grossman et al. will have fun giving it a try.