molecules

Teaching NMR Using Online Textbooks*

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Abstract: Nuclear magnetic resonance (NMR) spectroscopy has almost become an essential analytical tool for the chemist. High-resolution one- and multi-dimensional NMR, time-domain NMR, and NMR microscopy are but a few of the NMR techniques at a chemist's disposal to determine chemical structure and dynamics. Consequently, even small chemistry departments are finding it necessary to provide students with NMR training and experience in at least some of these techniques. The hands-on experience is readily provided with access to state-of-the-art commercial spectrometers. Instruction in the principles of NMR is more difficult to achieve as most instructors try to teach NMR using single organic or analytical chemistry book chapters with static figures. This paper describes an online textbook on NMR spectroscopy called The Basics of NMR (http://www.cis.rit.edu/htbooks/nmr/) suitable for use in teaching the principles of NMR spectroscopy. The book utilizes hypertext and animations to present the principles of NMR spectroscopy. The book can be used as a textbook associated with a lecture or as a stand-alone teaching tool. Conference participants are encouraged to review the textbook and evaluate its suitability for us in teaching NMR spectroscopy to undergraduate chemistry majors.

Keywords: Nuclear Magnetic Resonance, NMR, Magnetic Resonance Imaging, MRI, Educational Software.

Background

I try to involve undergraduates in my magnetic resonance research whenever possible. (See references [2-8] for examples of their work). A reoccurring problem is bringing students quickly up to speed on the principles of magnetic resonance so they can appreciate their research experience. An additional complication in the training process is that many of these students have not yet taken physical chemistry. Asking them to learn the dynamic principles of magnetic resonance from static diagrams in textbooks written for more advanced students is inappropriate, and teaching them the principles of magnetic resonance one-on-one is too time consuming.

My solution to this problem was to develop computer based instructional material tailored to their level and containing animated diagrams to help explain dynamic principles. These materials soon became popular with other instructors and students around the world and I found myself producing them as animated textbooks. The first book, produced in 1985, was written in Pascal for use on Microsoft DOS platforms [9].

Unfortunately, a new problem arose. Although the Microsoft DOS computers were popular, this platform choice prevented this material from reaching those students and educators using Apple and Unix computers. The introduction of platform independent hypertext markup language (html) browsers, and the availability of internet access presented a solution to this problem. Now all computer users could use this educational material.

There are a few additional advantages of html worth mentioning that led to the rapid generation of web based educational materials. The first is, coding in html is easier than programming in some of the other computer languages used to produce the Microsoft DOS based books. The second is, web browsers allow the user to view the html source code for the site being viewed. This feature allows an html coder to take advantage of one of the earliest acquired learning skills: how to copy! A programmer can readily see how another author or coder solved a problem and implement it.

My first web-based hypertext book was *The Basics of MRI* [10]. This book concentrated on magnetic resonance imaging (MRI), an imaging application of NMR. The popularity of this work convinced me to produce a second hypertext book entitled *The Basics of NMR* [11]. The html code for both *The Basics of NMR* and *The Basics of MRI* was written using a text editor. Admittedly, there are more powerful html editors for generating html code. These programs added more formatting peculiarities to the resultant html code that needed to be removed. In general, the time spent removing these peculiarities was greater than the time saved using the html editors.

Although the NMR book is the focus of this paper, the presentation style in the MRI book is the same. Many chemists find the MRI text interesting, and some biochemistry instructors teach MRI because of the chemical and dynamical information it provides. A description of organization and contents of the NMR hypertext book follows.

Organization

Navigation through the book starts at the cover page by clicking on an open button. The inside of the book is presented in three resizable frames that simultaneously display text, graphics, and navigation aids. The graphics or animation frame occupies the upper left side of the screen. This frame will be used to display animations, static figures, references, symbol definitions, and the glossary. The short-cut navigation window appears on the lower left side of the screen and has one line of options: Contents, Help, Glossary, and Symbols. The text frame is on the right half of the screen and displays the hypertext of the book. To experience the full potential of the frames, a screen capable of displaying at least 1024 by 768 pixels with 256 colors is recommended.
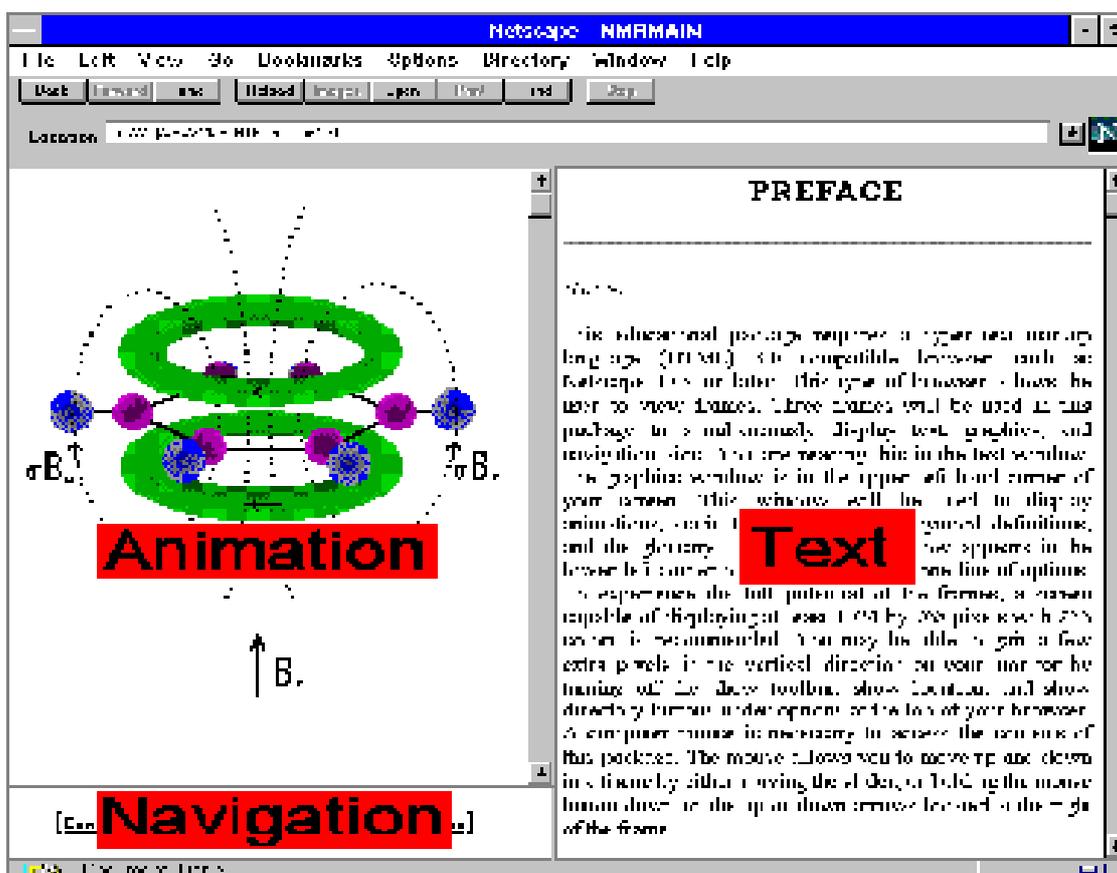

Figure 1. Position of the three frames in *The Basics of NMR*, © 1997 J.P. Hornak [11].

The content of this hyper-textbook is organized into 11 chapters. Each of the eleven chapters may be accessed by pointing to and clicking on the chapter title in the table of contents with the mouse. Each chapter has several sub-sections. The titles of the sub-sections are listed at the top of each chapter. The text of the chapter contains several underlined references to chapters in this book. Clicking on one of these will bring up the location in the new chapter containing the reference material.

There are over 60 terms defined in the glossary, and 75 symbols in a list of symbols. Both the symbols and glossary can be viewed in their entirety in the animation window by clicking on them in the table of contents. Each entry in the glossary contains a chapter reference. By clicking on this reference, you will bring up the chapter where the glossary entry is defined or first used. This feature makes the glossary also serve as an index. Readers may also search for a term in a chapter with the edit/find command of the browser.

Clicking on a reference symbol (■) in the hypertext brings up a reference in the graphics window. The reader may view the entire list of references by clicking on the references entry in the table of contents. The text contains several start (■) and play (▶) icons. These icons display images, figures, and animation in the animation/graphics window. The start icon displays single frame images and figures, while the play icon displays an animation. The bottom of each text page contains links to send the reader to the top of the current chapter, back one chapter, and ahead one chapter. There are occasional references to previous and future chapters in the text. When the word *chapter* and the accompanying number are underlined, you may click on the underlined material and go directly to that chapter.

This hypertext book has been organized so that background material and underlying principles are introduced first. Each chapter builds on the previous one. The very knowledgeable reader may elect to skip these chapters; however this is discouraged as often times nomenclature, conventions, and symbols are first presented in these introductory chapters.

The early versions of this book used gif images for the Greek symbols. Each symbol was individually created using Corell Photo Paint. Later additions to the book used the *FONT FACE="Symbol"* command to print Greek characters. As a consequence of this and the use of frames, this educational package requires a hypertext markup language (HTML) 3.0 compatible browser, such as Netscape Communicator 4.0x or later, or Microsoft Internet Explorer 3.0x or later. This type of browser allows the user to view frames.

One of the best aspects of web-based publications is their ability to be updated immediately, without waiting for a new edition to be published. The Basics of NMR is periodically updated with new material. Major revisions are indicated by a Roman numeral located at the bottom of the title page.

The site was Copyrighted with the United States Library of Congress in an attempt to protect the intellectual content and effort that went into creating the book. The site was also registered with the major web search engines on the day it was launched. This allowed readers to find the site within a few days of launch.

Contents

The eleven chapters of the hypertext book are organized and designed to slowly introduce the basic principles of NMR spectroscopy. The titles of the eleven chapters are found in Table 1.

Table 1. Chapters in *The Basics of NMR.*

1.	Introduction
2.	The Mathematics of NMR
3.	Spin Physics
4.	NMR Spectroscopy
5.	Fourier Transforms
6.	Pulse Sequences
7.	NMR Hardware
8.	Practical Considerations
9.	Carbon-13 NMR
10.	2-D Techniques
11.	Advanced Spectroscopic Techniques

The Introduction presents terminology and reviews units. The second chapter reviews the mathematics necessary to grasp the concepts presented in this book. This mathematics includes: exponential functions, trigonometric functions, differentials and integrals, vectors, matrices, coordinate transformations, convolutions, and imaginary numbers. The students are now ready to learn spin physics. This is the largest and most important chapter in the book because it sets the foundations for NMR spectroscopy. The spin physics chapter contains materials on: Spin, Properties of Spin, Nuclei with Spin, Energy Levels, NMR Transitions, Energy Level Diagrams, Continuous Wave NMR Experiment, Boltzmann Statistics, Spin Packets, T_1 Processes, Precession, T_2 Processes, Rotating Frame of Reference, Pulsed Magnetic Fields, Spin Relaxation, Spin Exchange, and the Bloch Equations. It is this chapter where the animations are first become necessary to describe a magnetic resonance phenomenon. Precession of a magnetization vector in the xy-plane is a good example of this. (See Figure 2.)
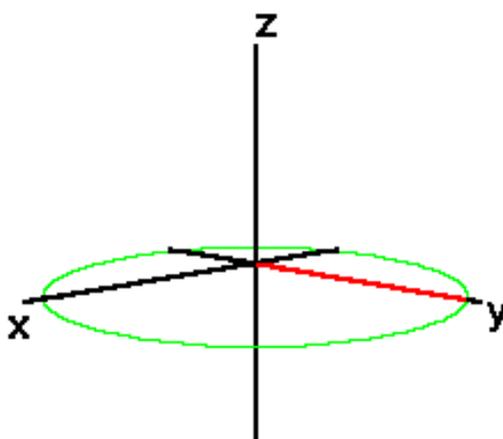

Figure 2. Precession of a magnetization vector in the xy-plane as portrayed in Chapter 3 of *The Basics of NMR*, © 1997 J.P. Hornak [11].

The students now have enough background to learn about the spectroscopic concepts of chemical shift, spin-spin coupling, and the time domain NMR signal, that are introduced in the next chapter on NMR spectroscopy. The Fourier transform (FT) is introduced next in a dedicated chapter. The concept of the FT was not introduced previously in the mathematics chapter because the reader did not have an appreciation of why it is needed. The FT is introduced at in such a way that anyone familiar with the basics of calculus can understand.

The hypertext book next presents simple pulse sequences used to record spectra and measure relaxation times. These include the 90-FID, spin-echo, and inversion recovery sequences. These sequences are presented with verbal descriptions, timing diagrams, and animated vector diagrams.

The NMR hardware chapter starts with a hardware overview. This is equivalent to what you might find in an organic chemistry book. The chapter also contains details on the magnet, field lock, shim coils, sample probe, RF coils, gradient coils, qadrature detector, and digital filtering. Some might argue that this is more detail then than is needed in an instrumentation chapter, but it allows me to explain questions in later chapters such as, *Why is signal averaging done in multiples of eight?* The chapter also contains information on NMR safety related to cryogens and magnetic fields.

The chapter entitled Practical Considerations is one of the most useful ones to a student. It discusses sample preparation, the exchange phenomenon, probe tuning, determining a 90° pulse, magnetic field shimming, phase cycling, recording 1-D hydrogen spectra, integration, signal-to-noise ratio improvement, variable temperature studies, and cryogen fills. The cryogen fills are described using real photographs of a Helium fill. A very useful part of this chapter is the troubleshooting guide. It contains a series of yes/no questions designed to help an individual isolate an NMR problem.

Carbon-13 NMR and two-dimensional (2-D) NMR are covered in separate chapters. The C-13 chapter describes the need for decoupling, what an inverted population is, the nuclear Overhauser effect, and simple one-dimensional (1-D) spectra. The 2-D chapter presents a clear example of how chemical shift and j-coupling information can be recorded by varying the echo time in a spin-echo sequence. The COSY sequence is also presented along with examples.

The final chapter in the text covers advanced spectroscopic techniques. These techniques include the measurement of diffusion coefficients and spin relaxation times, solid state NMR, NMR microscopy, and solvent suppression.

Feedback/Statistics

Most web servers create an access log for files it serves. These logs permit a statistical evaluation of the users of a web site. These logs were used to generate access statistics. Figure 3 displays the number of times *The Basics of NMR* was accessed per month since its introduction on the web 1 January 1998.

It is worth noting a few observations about this plot. The first is that usage increases after the introduction and registration of a site with search engines. This can be attributed to either: 1. the number of people using the web increasing, and/or 2. knowledge of the existence of the site spreads as once one person uses it. The latter is more likely the cause at this time.
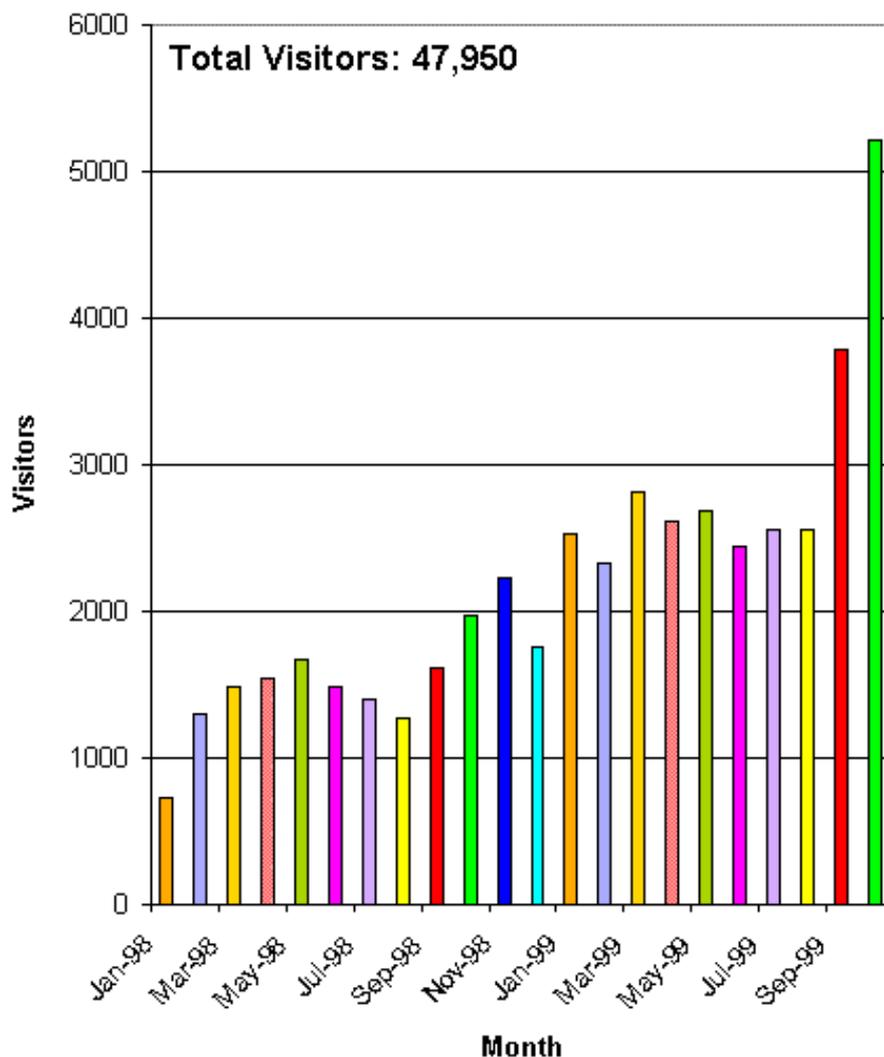
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A second more interesting observation is what the usage statistics show about our global society's use of the web for education. Usage peaks in March-April, decreases in August and then again but more slightly in December-January. Is the correlation between the low usage periods and the peak summer vacation season in the northern hemisphere, and the Christmas/New Year/Chanukah vacation period coincidental? Is there a correlation between the high usage period and the end of the academic year?

This trend is more pronounced in the usage statistics from *The Basics of MRI* (http://www.cis.rit.edu/htbooks/mri/), which has been in use since September 1996. (See Figure 4.)
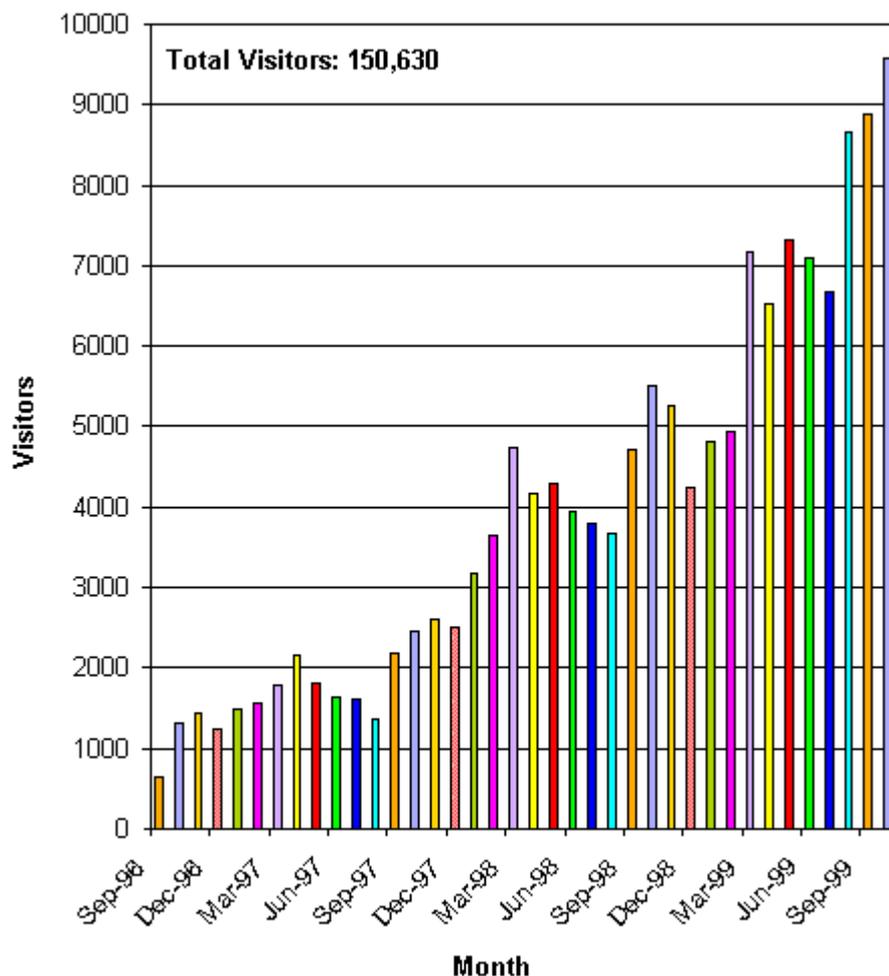
Figure 4. Number of times *The Basics of MRI* was accessed per month since September 1996.

Access logs also allow statistics to be tabulated on the user country of origin. The usage of *The Basics of MRI* by country has been tabulated and is presented in the Usage Statistics chapter of the book [10]. The majority of the users are from the USA. The number of users from other countries is increasing as internet access becomes more readily available in these countries.

Feedback on *The Basics of NMR* from students at the Rochester Institute of Technology is positive. Owing to the anecdotal nature of this feedback, it is not included here. Several e-mails have been received from readers of these books. Some of these are included here to provide a sense of who is utilizing the book and what their impressions are. When necessary, names and/or affiliations have been removed.

The following comments came in from educators and scientists.

I really liked your htbook on 'Basics of NMR' as a teaching aid. Please send me information on site licenses. ... Thanks

Brian Sykes, Professor of Biochemistry, University of Alberta

I like your work! I've been drawing some myself, but mostly because I hadn't seen anything like this on the web. I hope you recover some compensation for all your work. This is a valuable educational contribution. ... Anyway, nicely done!

Doug Mounce, Grant & Contract Svcs., University of Washington

Your hyper book on NMR is excellent and I am sure a lot of people will find it very useful.

S. Ganapathy, NMR Group, National Chemical Laboratory, Poona, India

I enjoyed your Webpage on the basic's of NMR. You have put together a great explanation of the fundamentals of NMR. ... Thanks.

Tim Volm, University of Iowa

I am making a transition to work on NMR of biomolecules. When I was browsing the web for basic information on NMR and I ran into you hypertext book on the basics of NMR. I really find the explanations very lucid and easy to understand.

T. Murlidharan Nair, Department of Medicinal Chemistry, University of Utah

I just found you web course on NMR. It is great. I'm a graduate student in Biochemistry and I am working in an NMR lab. I was looking for links for our web page. The graphics you have are wonderful. It really helps you visualize what is going on. I look forward to seeing how you expand it!

Karen Klenk, University of Maryland

Thanks for your excellent article. I am working on a complex issue, and part of it requires that I explain NMR to non-scientists. I had somewhat of an understanding of NMR prior to reading your article, but certainly not enough to boil it down to bare essentials. Your work did the trick!

Michael Tagg

One of the benefits of this hypertext book is the animated diagrams. They loose utility when reproduced in hard copy. Are readers missing this point, or is there benefit in the text that outweighs this shortcoming?

I was recently on the Internet when I came across your online book The Basics of NMR. I found it extremely useful and I would like to obtain a written or hard copy. Is this possible, and if so how do I go about getting it? Please email me with this information at your earliest convenience. Thank you in advance.

Frank, Florida State University

Some readers think very deeply about the material they are reading. The book makes the assumption that a 90° pulse width is much less than T_2 which is less than T_1. Because this was not clearly stated, Tore asked:

I have with great interest read your web-pages about NMR principles and reality. I would like to ask a rather simple question where I find that I don't know enough myself. I hope you can help: At which point in time during a 90-degree pulse has the macroscopic vector turned 90 degrees, and at what time does relaxation start to affect the vector? My interest is especially conserning frequency selective pulses. I am looking forward to your reply, Best regards,

Tore Skjetne, Senior Research Scientist, MR Center, SINTEF Unimed, NORWAY

Several students have sent in e-mail messages. Many express thanks for placing the material on the web.

I just wanted to express my sincere thanks for your online "textbook" on NMR. I am a fourth year student at Queen's University in Kingston, ON, Canada. I just finished a Spectroscopy course that did not have a course text because of the wide range of topics covered. The second half of the course was comprised entirely on NMR. I will definitely be referring back to your site as I prepare for my final exam. What a wonderful site! Thanks again.

Tanya, Student

I just wanted to let you know that I am very impressed by your website. It is informative and the graphics definitely complement the written material. I am fortunate to have a 17" Monitor and can view things simultaneously. I am a fourth year Chemistry student at Brock University and my interest lies with NMR. Once I had examined your site, I e-mailed my Professor and the other few (I say few as there is myself and one other student) students in my class so that they could take a look for themselves. ... I certainly wish that I had the money to buy a copy as I know myself and my classmates could definitly benefit. I look foreward to using the info in the future.

Paul

However, this student was a little too thankful.

Thanks to you, myself and one of my classmates will no longer fail the final paper which we have due two hours from now. Thank you. I intend to name my first-born child after you.

Thank you

Thank you

Thank you

Your humble supplicant,

Winston "Hornak is God" Timp

It was reassuring to see that some students are taught to obtain permission before reproducing copyrighted materials.

I am a senior in physics at South Dakota State University. I'm planning to present a 45 minute lecture on NMR in December. I was very impressed with the graphics in your lecture series, and would like your permission to use several of them in my lecture.

Gary Carlson

Many students ask for help on NMR related topics that were not cover in the book.

Hi, my name is Jim. I've been doing research on the history of physics, and I'd like to know how long NMR has been actively used. Specifically, was this technology available in the 1970s? Thanks in advance,

Jim, berkeley.edu

At least he was grateful to receive a reply.

Fastest e-mail response ever recorded. You the man!

Jim, berkeley.edu

Many e-mail messages are received from students that are in a hurry, and as a consequence, may not have time to read or think for themselves.

i have an NMR spectrum of two monosaccharides, but i cannot read them, can u help? i dont know when u can get back to me but its sat if u can get back to me today or sunday if not thanks anyway
Gary, mediaone.net

This e-mail sent by Amy in the UK on Sunday evening at 8:30 PM.

Can you tell me how the signal is generated as I need to know for my Biochemistry exam on Wednesday. Any help would be appriciated. Thank you.

This e-mail came in from someone at aol.com who only wanted to be known as chm student.

I am a chem student and I have a question about an HNMR with a hill at 10.1 integrated to 1 and a singlet at 2.5 integrated to 3. and thats it. I think it is an aldehyde with an isolated CH3 thats it. I was wondering if you would agree with me. Thank You,
chm student

Some e-mail messages come from a more general audience. This message came from an individual that never knew of NMR spectroscopy.

I read sections of your book online and find it to be quite fascinating. The company I work for is interested in analyzing the quality of their packaging process...
Michael, aol.com

Every so often one of these e-mail messages arrive. Is it truly an honor, or a request to advertise their service on my page?

Congratulations! Your The Basics of NMR site at http://www.cis.rit.edu/htbooks/nmr/ has been chosen as HMS Beagle's "Web Pick of the Day", and will be featured on our home page within the next few days with a link to your site. Your site will then be listed on Beagle's "Favorite Web Sites" page for 30 days, as well as permanently catalogued in BioMedLink (http://biomedlink.com), our comprehensive, evaluated database of biological and medical websites.

HMS Beagle is a webzine for biological and medical researchers, with a daily digest of the highest-quality Web resources and published material. We were recently selected as one of Yahoo's top 32 "incredibly useful" Web sites, and have thousands of visitors daily.

Please place a reciprocal link back to our Home Page at: http://hmsbeagle.com

You can also download our "HMS Beagle Web Pick button" and read linking instructions at: http://biomednet.com/hmsbeagle/current/main/citing.htm#linking
Lois Wingerson, Editor HMS Beagle

Please, do not take my previous comment the wrong way, these sites provide a valuable service: they separate the wheat from the chaff on the web. Many search engines catalog and provide links to everything in a site. Therefore, they often do not direct readers to your intended starting point in a book. A smart cataloging service on a search engine will eliminate this problem. Zac was probably unable to access the whole book for this reason. He found the information he needed after being directed to the front cover.

My name is Zac and I am a college student at SUNY Brockport with an intended chemistry major. I was having a little difficulty with the concepts of Nuclear Magnetic Resonance spectroscopy and was looking on the internet for some help. Then I found your page. I found it helpful, but I am still having some difficulty understanding how to determine the compounds that created the spectra in NMR. In other words I am having difficulty reading the spectra chart and determining which compounds made it and what order they go in. Can you offer me any advice on how to pick up some key points to this subject? Is there any literature you are aware of that is available and would help me? I have "Solomons: Organic Chemistry 6th Edition." So far it has been vague and hard to understand. Any advice you could give me would be appreciated. Thank you for your time.
Zac, hotmail.com

These e-mail messages are typical of the ones received daily. Some authors might conclude there are dangers in posting a personal e-mail address on a web book. Would you? I have kept mine on both books. E-mail messages to the NMR site are a little easier to deal with then the MRI site, where readers sometimes ask for medical advice on an ill child or relative.

Summary

I have published two hypertext books on the web, one on NMR spectroscopy (*The Basics of NMR*) [11], and the other on magnetic resonance imaging (*The Basics of MRI*) [10]. Many readers have found these books useful. I encourage you to examine the material.

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