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REVIEW

Photosynthesis and the Web: 2008

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Abstract The World Wide Web has become an important resource for public awareness and for educating the world's population, including its political leaders, students, researchers, teachers, and ordinary citizens seeking information. Relevant information on photosynthesis-related web sites is grouped into several categories: (1) group sites, (2) sites by subject, (3) individual researcher's sites, (4) sites for educators and students, and (5) other useful sites.

Keywords Internet · K-12 education · World Wide Web

Abbreviations

ASU	Arizona State University
HTML	Hyper Text Markup Language
ISPR	International Society of Photosynthesis Research
NCSA	National Center for Supercomputing Applications
PDF	portable document format
UIUC	University of Illinois, Urbana-Champaign
URL	Universal Resource Locator
WWW	World Wide Web

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Introduction

The World Wide Web (WWW) has become a very important resource for public awareness and for educating the world's population, including its political leaders, students, researchers, teachers, and ordinary citizens seeking information. In 1999, we wrote a short survey of the various photosynthesis sites found on the web (Orr and Govindjee 1999). Although many fine sites were found and discussed, the number of sites was rather limited due to the inexperience of scientists with hypertext markup language (HTML), lack of reliable web server hardware, constantly changing web addresses, and difficulty in using the search engines available at the time. Within a few years the web had grown exponentially, many more sites had appeared and were much easier to find as web search engines matured. In fact, in a later review (Orr and Govindjee 2001), we found there were too many sites to list all of them. We decided to highlight only a sample of those sites that we felt presented good, quality information in an interesting manner. We follow the same criteria here.

This review presents relevant information on photosynthesis-related web sites grouped into several categories: (1) group sites, (2) sites by subject, (3) individual researcher's sites, (4) sites for educators and students, and (5) other useful sites. Due to time and length restrictions, as well as the dynamic nature of the Web, it is impossible to include every worthy web site in this review. Thus, we will highlight a few of the sites that we think epitomize the best the Web has to offer. Sites chosen for discussion will usually have a significant amount of information on one or more photosynthesis research areas and may include illustrations, movies, and links to other sites of importance. Our sincere apologies to anyone whose site we have overlooked. (If the reader is aware of any good sites that are not mentioned in this article, we (larry.orr@asu.edu and gov@uiuc.edu) would like to be informed so we can include it in our web-based version of this review.)

In this review we provide links to many websites and web pages and to a few portable document format (PDF) documents. For the most part, we are concerned primarily with sites that can be easily accessed directly from a browser. PDF files generally have to be downloaded to a local computer and then opened in a secondary program, depending on the browser used and the manner in which the computer is set up, which makes them somewhat inconvenient. Many of the sites we have listed will have links to PDF files, often to journal papers that can be accessed by schools that subscribe to the electronic journals online, but which are not necessarily available to the general public. We have decided that most of those PDF documents are outside the scope of this review, though we have included some which contain information not found elsewhere and which do not require special subscriptions.

The contents of this review also appear in a companion website which may be found at http://photoscience.la.asu.edu/photosyn/photoweb/default.html and mirrored at http://www.life.uiuc.edu/govindjee/photoweb/.

Group sites

One of the largest group sites, the Arizona State University (ASU) Photosynthesis Center site, went online in 1995. It was developed and is currently maintained by one of us (LO) and can be accessed at http://photoscience.la.asu.edu/photosyn/. This award-winning site is very comprehensive and showcases not only the operations and work of the Center, but also provides original material and numerous annotated links to individual and group photosynthesis research sites of interest to researchers, educators, students, and the general public. One of its most popular items is the educational section that contains links to sites of interest to students and educators and has been annotated as to subject matter and appropriate age-level of understanding (http://photoscience.la.asu.edu/photosyn/education/learn.html). Another popular item is the Nicelist, a list of photosynthesis researchers who don't mind receiving and answering emails (hence they are ''nice'') and includes their email addresses and, in most cases, their web site URLs (http://photoscience.la.asu.edu/photosyn/nicelist.html). Some of the Center's other web pages will be mentioned in the other sections. Recently, the Center expanded its areas of interest to include bioenergy research into alternative fuels derived from photosynthetic bacterial biomass, the production of hydrogen from photosynthetic-influenced model systems, and participation with other ASU initiatives to study climate change and energy sustainability issues at the scientific and public policy levels. In recognition of this evolution, the Center has changed its name to the ASU Center for Bioenergy and Photosynthesis, though it will still be known to us as the Photosynthesis Center. An artistic representation of the promise of bioenergy from photosynthesis is shown in Fig. 1.

The University of Illinois at Urbana-Champaign (UIUC), home of the National Center for Supercomputing Applications (NCSA) and Mosaic (and therefore the ''mother'' of all modern web browsers), hosts several important sites. A site by one of us (G) (http://www.life.uiuc.edu/govindjee/), is much more than an individual site as it includes information on a variety of topics, including course web pages, a major tutorial/essay on ''The Photosynthetic Process'' (by J. Whitmarsh and Govindjee), movies, photos and several items of historical importance including PDF files of Personal Perspectives of some eminent scientists, as well as some obituaries, and brief comments on Robert Emerson, Eugene Rabinowitch, William Arnold, Lou Duysens, and Stacy French. There is also a tutorial on ''Photosynthesis and Time'' and other teaching materials such as slides which can be used in the classroom. A significant new addition is the availability of the complete references of all the chapters in Volumes 1–25 of Govindjee's Series 'Advances in Photosynthesis and

Fig. 1 Artist's representation of the power of green—the transfer of solar energy through photosynthesis to provide bioenergy for all living things. From the Center for Bioenergy and Photosynthesis, http://photoscience.la.asu.edu/photosyn/. Artwork by Michael Hagelburg, Arizona State University, used by permission

Respiration' (Springer) (http://www.life.uiuc.edu/govindjee/Reference-Index.htm). UIUC is also the home of the wonderful and highly educational site of A. R. Crofts (http://www.life.uiuc.edu/crofts/ahab/index.html). The Photosynthesis Research Unit (http://www.ars.usda.gov/main/docs.htm?docid=3333), affiliated with the United States Department of Agriculture (USDA) Agricultural Research Service, covers many areas of photosynthesis crop research. The Theoretical Biophysics Group at UIUC is also present with an excellent site (http://www.ks.uiuc.edu/) with many important pages including ''Quantum Biology of the Photosynthesis Unit'' (http://www.ks.uiuc.edu/Research/psu/psu.html), animations of various structures (http://www.ks.uiuc.edu/Overview/movie_gallery/), and much more.

The Biology group of John Allen at Queen Mary London, UK (http://jfa.bio.qmul.ac.uk/~john/webstar/index.html) contains much useful information and links as well as interesting pages on ''Light, Time and Micro-Organisms'' (http://jfa.bio.qmul.ac.uk/~john/webstar/ltm/default.html), imaging chlorophyll fluorescence, and much more.

Uppsala University, located in Sweden, is the home of the Photosynthesis Group (http://www.fotomol.uu.se/Forskning/Biomimetics/fotosyntes/index.shtm), led by Stenbjörn Styring, which studies Photosystem II and artificial photosynthesis.

The Photosynthesis Group at the University of Southern Denmark (Odense University) maintains a site about their work with light-harvesting antennas of green photosynthetic bacteria (http://www.sdu.dk/Nat/bmb/groups/photo/index.html).

The Department of Biophysics at Leiden University, The Netherlands (http://www.biophys.leidenuniv.nl/) hosts information about several important subjects. Follow the numbered links at that site to find information about ''Mechanism of Oxygen-Evolution in Photosynthesis,'' ''Single-Molecule Spectroscopy of Pigment-Protein Complex,'' and ''Physics of Photosynthetic Reaction Centers.''

The Photosynthesis Group at Göteborg University, Sweden, has a nice site with detailed descriptions of their work with plastocyanin and other areas of photosynthesis (http://www.bcbp.gu.se/photosyn/). The Avron-Wilstätter Center for Photosynthesis Research is located at the Weizmann Institute of Science (http://www.weizmann.ac.il/acadaff/Scientific_Activities/current/wilstatter_center.html) and is working with several groups to study many areas of photosynthesis.

The Chemistry Division of Argonne National Laboratory, Illinois, is working on several areas of photosynthesis (http://chemistry.anl.gov/photosynthesis/index.html).

The Robert Hill Institute, Centre for Photosynthesis Research at the University of Sheffield, UK (http://www.photosynth.org/) has links to several of the researchers working at the Institute.

Acad. M. Popov Institute of Plant Physiology, Dept. of Photosynthesis, Bulgarian Academy of Sciences (http://www.bio21.bas.bg/ipp/photosynth/photosynth.html) is conducting research on biophysical, biochemical, and ecological aspects of photosynthesis and photorespiration in higher plants.

The Institute of Basic Biological Problems, Dept. of Photobiology, Russian Academy of Sciences [formerly the Institute of Soil Science and Photosynthesis] (http://www.ibbp.psn.ru/engl/index.php?option=com_content&task=blogcategory&id=71&Itemid=80) conducts research in several important areas. The connection to this site is often very slow, so be patient.

Sites by subject

Broad overview sites

There are several sites devoted to the entire photosynthetic process. Although they may cover the same subject, the articles are written for a variety of audiences. Some are basic narratives aimed at the general public, others are comprehensive courses aimed at college students. All of these are quite good and several should be checked out for comparison.

''The Photosynthetic Process'' by John Whitmarsh and Govindjee (http://www.life.uiuc.edu/govindjee/paper/gov.html) is a comprehensive chapter that covers photosynthesis history and every facet of photosynthesis research in a relatively detailed manner.

Wim Vermaas at ASU has written ''An Introduction to Photosynthesis and Its Applications'' (http://photoscience.la.asu.edu/photosyn/education/photointro.html) which is a good introduction for the general public.

J. M. Farabee from Estrella Mountain Community College has written a highly recommended online biology course text that includes a detailed section on photosynthesis with emphasis on the physical aspects of the process. He also includes review questions, learning objectives, and a nicely done illustrated glossary (http://www.emc.maricopa.edu/faculty/farabee/BIOBK/BioBookPS.html).

Members of the Faculty of Biology at the University of Hamburg, Germany, have also produced an online botany textbook with excellent section devoted to photosynthesis (http://www.biologie.uni-hamburg.de/b-online/e24/24.htm).

Kapiolani Community College in Hawaii has a web site devoted to the chemical equations of photosynthesis (http://library.kcc.hawaii.edu/external/chemistry/everyday_photosyn.html).

Although the online Encyclopaedia Britannica is only available by subscription, the entire 36-page section on photosynthesis is available at no cost through a link on the Photosynthesis Center educational resources page as the Center is a recognized Britannica iGuide site (http://photoscience.la.asu.edu/photosyn/education.html).

Wikipedia has extensive coverage of the entire process with many links at http://en.wikipedia.org/wiki/Photosynthesis. Both authors of this review have participated in the editing of the Wikipedia. Please note that the Wikipedia is a work in progress and is far from perfect. Due to its open communal editing process, not all information is entirely accurate and much more space is devoted to items of interest to those that edit the Wikipedia, i.e., current popular culture such as rock groups, movie stars, etc., than science. Still, it is a good place to look for quick information even on scientific subjects, though it is recommended that another source always be checked before relying completely on its contents for one's research. If you have the time, we encourage everyone to open a no-charge editorial account and help maintain this interesting venture.

June B. Steinberg's site at http://faculty.nl.edu/jste/photosynthesis.htm has easy-to-understand explanations and links to more detailed information. There are many useful animations.

Molecular Expressions at Florida State University has a wonderful animated web page as part of its ''Optical Microscopy Primer'' (http://micro.magnet.fsu.edu/primer/java/photosynthesis/index.html). There is much here to enjoy and it is fun to roam around through the site. For example, see the section on ''Light and Color'' (http://micro.magnet.fsu.edu/primer/lightandcolor/index.html) which defines and explains what light is and concepts such as fluorescence, reflection, refraction, human perception of color, lasers, etc. A truly wonderful sight.

FT Exploring has a wonderful site, ''Photosynthesis: How Life Keeps Going...and Going...and Going..., for students (http://www.ftexploring.com/photosyn/photosynth.html). It covers the details of photosynthesis and how it relates to the rest of life. There is much good information here, as well as good humor and illustrations.

Specific subject sites

There are many sites that specialize in a certain aspect of photosynthesis. Here are some of the best arranged by topic. There will be several sites that overlap somewhat and some may appear in more than one group.

History of photosynthesis/biographies/Nobel prizes

''Milestones in Photosynthesis Research'' by one of us (G) (http://www.life.uiuc.edu/govindjee/papers/milestones.html) explores many aspects of photosynthesis in a historic manner.

Another paper, ''Carotenoids in Photosynthesis: An Historical Perspective,'' explores the history of the study of carotenoids using numerous personal observations by one of the authors (G) who participated in many of the activities (http://www.life.uiuc.edu/govindjee/papers/CarFin1.html). Both of these papers contain numerous references and anecdotes about pioneers in the field that can be found nowhere else.

A list of historical articles, published in Photosynthesis Research, are available at: http://www.life.uiuc.edu/govindjee/history/articles.htm. Further, PDF files of articles by Howard Gest (on Ingenhousz); Herb Dutton (on the discovery of energy transfer from carotenoids to chlorophyll); and Govindjee (on the quantum yield controversy between Emerson and Warburg) are also available at this site.

Other important historical documents are:

''Nobel Prize Winner in Photosynthesis Research'' (http://www.life.uiuc.edu/govindjee/history/nobel-ps.htm) is a list of the many researchers who have won the Nobel Prize while or before studying photosynthesis.

''Personal Perspectives in Photosynthesis Research'' (http://www.life.uiuc.edu/govindjee/perspectives.html) is a list of the Personal Perspectives, autobiographical retrospectives, that have appeared in the international journal *Photosynthesis Research*. Although these perspectives usually do not contain large amounts of science, they do discuss the major discoveries by some well-known researchers. In particular, they contain the personal reflections, memories, and the obstacles the authors had to overcome and other surprises. For example, the Personal Perspective of David Walker begins, ''This is the story of a young man who wished to go to sea like his father and finished up, instead, in photosynthesis.'' They are great reading and tell about scientific research the way it really is. 111 of these perspectives by 132 authors in 19 countries have been collected in a recent book, *Discoveries in Photosynthesis*, edited by Govindjee, J. Thomas Beatty, Howard Gest, and John F. Allen (http://www.life.uiuc.edu/govindjee/newbook/Vol%2020.html). A few of the perspectives are available as PDF files (please note that the first page of each file may be blank):

David Krogmann (http://www.life.uiuc.edu/govindjee/history/KrogmannDavidPP.pdf);

R. Clint Fuller (http://www.life.uiuc.edu/govindjee/history/FullerClintPP.pdf);

Giorgio Forti (http://www.life.uiuc.edu/govindjee/history/FortiGeorgioPP.pdf);
André Jagendorf (http://www.life.uiuc.edu/govindjee/history/JagendorfAndrePP.pdf);
George Feher (http://www.life.uiuc.edu/govindjee/history/FeherGeorgePP.pdf);
David Walker (http://www.life.uiuc.edu/govindjee/history/WalkerPP.pdf)

Govindjee has also edited several obituaries that have been published (http://www.life.uiuc.edu/govindjee/history/obituaries.htm), with some of them available online as PDF files.

Carmen Giunta has collected excerpts from historically important papers and published them on his ''Classic Chemistry'' web site. These include papers by Jan Ingenhousz (http://webserver.lemoyne.edu/faculty/giunta/Ingenhousz.html), Antoine Lavoisier (http://webserver.lemoyne.edu/faculty/giunta/lavoisier1.html), and Joseph Priestley (http://webserver.lemoyne.edu/faculty/giunta/phlogiston.html).

A brief biography of Joseph Priestley can be found at http://www.chemistry.mtu.edu/~pcharles/SCIHISTORY/JosephPriestley.html. A brief biography of Jan Ingenhousz can be found at http://www.chemheritage.org/explore/life-ingenhousz.html and http://www.newadvent.org/cathen/16046b.htm.

The Nobel Prize site has pages devoted to all Nobel laureates. Some of interest to photosynthesis are:

Richard Martin Willstätter, Chemistry, 1915, won the prize for his research on chlorophyll and other plant pigments (Fig. 2). His biography is at: http://www.nobel.se/chemistry/laureates/1915/willstatter-bio.html.

James Franck, Physics, 1925, won for his work (with Gustav Hertz) on electron-atom collisions; later he developed the principle known as the Franck-Condon principle which is often used in physical description of early events in photosynthesis. See (http://www.nobel.se/physics/laureates/1925/press.html) and his biography (http://www.nobel.se/physics/laureates/1925/franck-bio.html).

Fig. 2 Richard Martin Willstatter, Nobel laureate in Chemistry, 1915. From the Nobel Prize web site, http://nobelprize.org/nobel_prizes/chemistry/laureates/1915/willstatter-bio.html

Chandrasekhara Venkata Raman, Physics, 1930, won his prize for his work on spectroscopy and the effect that now bears his name, Raman spectroscopy, which is used by many photosynthesis researchers: (http://www.nobel.se/physics/laureates/1930/press.html). His biography is at (http://www.nobel.se/physics/laureates/1930/raman-bio.html).

Hans Fischer, Chemistry, 1930, won for his work on porphyrins and blood and leaf pigments, particularly chlorophyll: http://www.nobel.se/chemistry/laureates/1930/press.html. His biography is at (http://www.nobel.se/chemistry/laureates/1930/fischer-bio.html).

Otto Heinrich Warburg, Physiology or Medicine, 1931, won for his work on respiration and the identification of the respiratory enzyme: http://www.nobel.se/medicine/laureates/1931/press.html. His biography is at (http://www.nobel.se/medicine/laureates/1931/warburg-bio.html). Warburg's insistence that the measured minimum quantum requirement for the evolution of one oxygen molecule in photosynthesis is 2.8–4 was proven to be wrong; it was shown to be 8–12, mainly by Robert Emerson and his students including one of us (G).

Paul Karrer, Chemistry, 1937, won for his work on carotenoids, flavins, and vitamins: http://www.nobel.se/chemistry/laureates/1937/press.html. His biography is at (http://www.nobel.se/chemistry/laureates/1937/karrer-bio.html).

Richard Kuhn, Chemistry, 1938, won for additional work on carotenoids and vitamins: http://www.nobel.se/chemistry/laureates/1937/press.html. His biography is at (http://www.nobel.se/chemistry/laureates/1938/kuhn-bio.html).

Severo Ochoa, Physiology or Medicine, 1959, won for his work on enzymatic processes in biological oxidation and synthesis and the transfer of energy. His biography is at (http://www.nobel.se/medicine/laureates/1959/ochoa-bio.html).

Melvin Calvin, Chemistry (Fig. 3), 1961, won for his work on carbon dioxide assimilation in photosynthesis, the carbon cycle, also named ''The Calvin Cycle'' after him: http://www.nobel.se/chemistry/laureates/1961/press.html. It is important to mention that Andrew Benson contributed heavily to this work, and the authors of this article prefer to call the cycle, ''Calvin-Benson'' cycle. (We refer the readers to consult A. A. Benson (2005) in ''Discoveries in Photosynthesis,'' pp 793–813, Springer, for his contributions.). Calvin's biography is at: (http://www.nobel.se/chemistry/laureates/1961/calvin-bio.html). Also, an obituary may be found at: http://www.lbl.gov/Science-Articles/Archive/Melvin-Calvin-obit.html; and another one at:

Fig. 3 Melvin Calvin, Nobel laureate, Chemistry, 1961, from http://www.lbl.gov/Science-Articles/Archive/Melvin-Calvin-obit.html

http://www.life.uiuc.edu/govindjee/history/obit/ObitMelvinCalvin.pdf. Jeffery Kahn writes about the establishment of the Calvin Photosynthesis Group project at UC Berkeley's Bancroft Library (http://www.lbl.gov/Science-Articles/Archive/Calvin-history-project.html). More information from the Library is available at http://bancroft.berkeley.edu/Exhibits/Biotech/calvin.html.

Robert Burns Woodward, Chemistry, 1965, won for the total synthesis of chlorophyll, vitamin B12, and other natural products: http://www.nobel.se/chemistry/laureates/1965/press.html. His biography is at: (http://www.nobel.se/chemistry/laureates/1965/woodward-bio.html).

George Porter, Chemistry, 1967, won for his development of flash photolysis (along with Ronald Norrish). Lord George Porter later did work on aromatic molecules and chlorophyll, energy transfer in photosynthesis and primary photochemistry of photosynthesis in femtosecond–picosecond time scale: http://www.nobel.se/chemistry/laureates/1967/press.html. His biography is at: (http://www.nobel.se/chemistry/laureates/1967/porter-bio.html).

Peter D. Mitchell, Chemistry, 1978, won for his work on biological energy transfer through the formulation of the chemiosmotic theory: http://www.nobel.se/chemistry/laureates/1978/press.html. His biography is at: (http://www.nobel.se/chemistry/laureates/1978/mitchell-bio.html).

Aaron Klug, Chemistry, 1982, won for development of crystallographic electron microscopy and his structural elucidation of biologically important nucleic acid–protein complexes: http://www.nobel.se/chemistry/laureates/1982/press.html. His autobiography is at: (http://www.nobel.se/chemistry/laureates/1982/klug-autobio.html).

Jean-Marie Lehn, Chemistry, 1987, won for his work on mimicking natural processes such as photosynthesis and for doing the groundwork for small synthetic structures called ''molecular devices'': http://www.nobel.se/chemistry/laureates/1987/press.html. His autobiography is at: (http://www.nobel.se/chemistry/laureates/1987/lehn-autobio.html).

Johann Deisenhofer, Robert Huber, and Hartmut Michel, Chemistry, 1988, won, for determining the three-dimensional structure of bacterial reaction center using X-ray crystallography. A description of their work can be found at: http://www.nobel.se/chemistry/laureates/1988/press.html. Deisenhofer's autobiography is at: (http://www.nobel.se/chemistry/laureates/1988/deisenhofer-autobio.html). Huber's is at: (http://www.nobel.se/chemistry/laureates/1988/huber-autobio.html). And Michel's is at: (http://www.nobel.se/chemistry/laureates/1988/michel-autobio.html).

Rudolph Marcus, Chemistry, 1992, won for his contributions to the theory of electron transfer reactions in chemical systems, including photosynthesis: http://www.nobel.se/chemistry/laureates/1992/press.html. His autobiography is at: (http://www.nobel.se/chemistry/laureates/1992/marcus-autobio.html).

Michael Smith, Chemistry, 1993, won for his fundamental contributions to the establishment of oligonucleotide-based, site-directed mutagenesis and its development for protein studies which has become a common technique for studying photosynthesis organisms: http://www.nobel.se/chemistry/laureates/1993/press.html. His autobiography may be found at: http://www.nobel.se/chemistry/laureates/1993/smith-autobio.html.

Paul D. Boyer and John E. Walker, Chemistry, 1997, won for their elucidation of the enzymatic mechanism underlying the synthesis of adenosine triphosphate (ATP): http://www.nobel.se/chemistry/laureates/1997/press.html. Boyer's autobiography is at: (http://www.nobel.se/chemistry/laureates/1997/boyer-autobio.html), and Walker's is at: (http://www.nobel.se/chemistry/laureates/1997/walker-autobio.html).

Ahmed H. Zewail, Chemistry, 1999, won for his studies of the transition states of chemical reactions using femtosecond spectroscopy: http://www.nobel.se/chemistry/laureates/1999/press.html. His autobiography may be found at: http://www.nobel.se/chemistry/laureates/1999/zewail-autobio.html.

The light reactions

From the Botany Online site at the University of Hamburg (http://www.biologie.uni-hamburg.de/b-online/e24/24c.htm), we get a brief history of the elucidation of the dark and light reactions. This is followed by an excellent description of phosphorylation and the two photosystems. The site is profusely illustrated.

''Photosynthesis and Time'' by Govindjee and Matej Lexa (http://www.life.uiuc.edu/govindjee/ptime/): The time sequence of the light reactions of photosynthesis are taught through a ''click-on'' window (with the four protein complexes in it), and through a movie. A clock covers the reactions from femtoseconds to milliseconds (recommended for all undergraduates and graduate students).

The Z-Scheme (Fig. 4) is the crux of the light reactions of photosynthesis. A simplified scheme and its description are presented at http://www.life.uiuc.edu/govindjee/text-zsch.htm. [For the scheme itself, see http://www.life.uiuc.edu/govindjee/ZSchemeG.html].

June Steinberg from National-Louis University has created animations to explain the light reactions using cyclic (http://faculty.nl.edu/jste/photosynthesis.htm) and non-cyclic (http://faculty.nl.edu/jste/noncyclic_photophosphorylation.htm) photophosphorylation.

Light-independent reactions (dark reactions)/Calvin-Benson cycle/carbon cycle

From the Botany Online site at the University of Hamburg (http://www.biologie.uni-hamburg.de/b-online/e24/24a.htm): This is a great site as the equations and the chemical structures are available. You may need to install some plug-ins.

From June B. Steinberg of National-Louis University (http://faculty.nl.edu/jste/calvin_cycle.htm): A beautifully done site; the steps are clearly shown. It requires downloading plug-ins.

From Smith College, here are interesting animations showing the various steps (http://www.science.smith.edu/departments/Biology/Bio231/calvin.html).

Joyce J. Diwan at Rensselaer Polytechnic Institute has a site with a very detailed explanation with numerous illustrations and links to PowerPoint presentations and test questions at http://www.rpi.edu/dept/bcbp/molbiochem/MBWeb/mb2/part1/dark.htm.

Wikipedia has a good article on the Calvin-Benson cycle (http://en.wikipedia.org/wiki/Calvin_cycle).

The photosynthetic unit/reaction centers

''Quantum Biology of the PSU'' from the Theoretical and Computational Biophysics Group at UIUC (http://www.ks.uiuc.edu/Research/psu/psu.html): It is a great site showing beautiful structures of antenna of bacterial systems (Fig. 5).

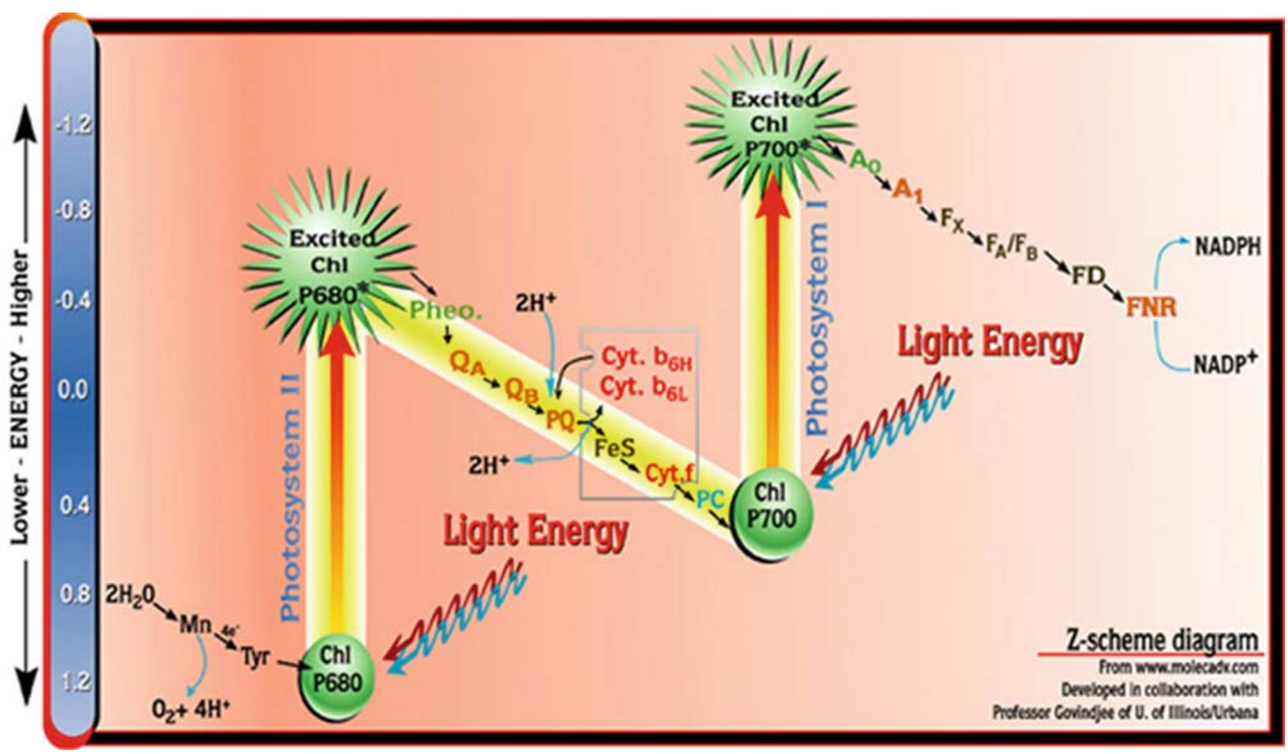

Fig. 4 A simple Z-scheme diagram of photosynthesis from http://www.life.uiuc.edu/govindjee/ZSchemeG.html. Courtesy of Wilbert Veit

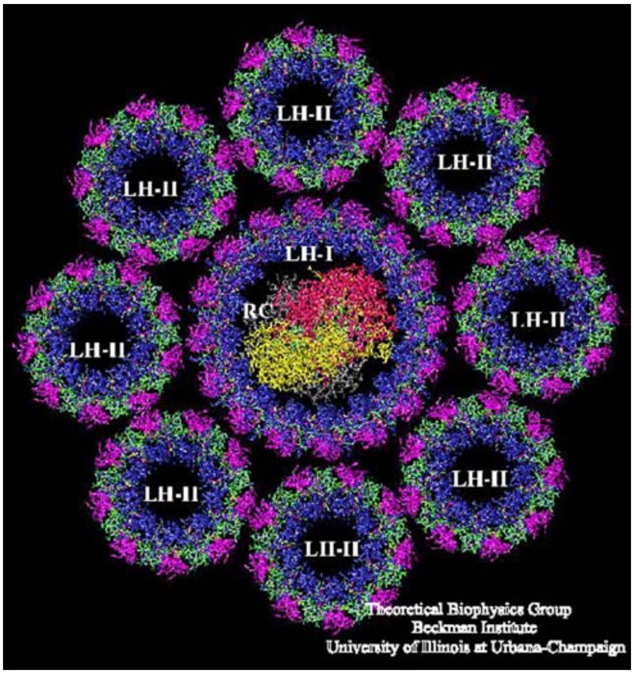

Fig. 5 Structure of the photosynthetic unit from http://www.ks.uiuc.edu/Research/psu/psu.html

''Schematic Diagram of a Photosynthetic Unit Showing Exciton Transfer'' is an animated web page from the University of Hamburg (http://www.biologie.uni-hamburg.de/b-online/library/bio201/psunit.html): It is lovely to watch it.

A press release for the 1988 Nobel Prize in Chemistry from the Royal Swedish Academy of Sciences, announcing the determination of the 3D structure of a photosynthetic reaction center (http://nobelprize.org/nobel_prizes/chemistry/laureates/1988/press.html). The text is great, but the figures are only in black and white.

The Roger Hangarter lab at Indiana University (http://www.bio.indiana.edu/~hangarterlab/courses/b373/lecturenotes/photosyn/et.html) contains a brief overview and some more complex details of the 'Photosynthetic Unit.'

''Photosynthetic reaction centres of purple bacteria'' from Scripps (http://metallo.scripps.edu/PROMISE/PRCPB.html) gives detailed structures from the PROMISE data base.

''Systems Biology of Photosynthesis in Dynamic Light Environment'' (http://www.e-photosynthesis.org) is a project to ''offer an open web platform for modeling and reverse engineering of photosynthetic dynamism.'' It is a major project and includes online experiments to view results.

Light-harvesting/antennas

''Photosynthetic Antennas and Reaction Centers: Current Understanding and Prospects for Improvement,'' by Robert E. Blankenship at Washington University St. Louis (written while he was at ASU) (http://photoscience.la.asu.edu/photosyn/education/antenna.html). It is a well-done text with basic diagrams. We recommend it to all students.

''Light Harvesting Complex II of photosynthetic bacteria'' from the Theoretical and Computational Biophysics Group (TCBG) at UIUC (http://www.ks.uiuc.edu/Research/bio_ener/LH_2/) and also ''Inter-Complex Excitation Transfer in photosynthetic bacteria'' (http://www.ks.uiuc.edu/Research/psu/psu_inter.html). Excellent colored versions of the antenna complexes in photosynthetic bacteria; links are provided to PDF files of three of their research papers.

''Organization of energy transfer networks in photosynthesis'' (http://www.ks.uiuc.edu/Research/psres/) also from the TCBG (above) compares light-harvesting mechanisms of anoxygenic and oxygenic photosynthetic bacteria.

''Light Harvesting Complex II of Purple Bacteria'' from Scripps (http://metallo.scripps.edu/promise/LH2PB.html). This site contains an excellent description and an extensive bibliography of the light-harvesting complex II of purple bacteria.

''Light-Harvesting in Bacterial Photosynthesis'' from Glasgow University Protein Crystallography group (http://www.chem.gla.ac.uk/protein/LH2/lh2.html): Though rather brief and somewhat jarring in its color choices for the text, it does have a brief description and links to nice pictures on structure and function of the antenna system in bacteria.

''Chloroplast Light-harvesting Complex II'' from Queen Mary College, London, UK (http://jfa.bio.qmul.ac.uk/~john/webstar/Research/lhcii_chime.html): A beautiful site to visit; it is highly recommended. You can download Chime and RasMol and watch the molecule while listening to Bach's Fugue in G major.

Electron transfer

''Electron Transport and Energy Transduction'' by John Whitmarsh at UIUC and the USDA Agricultural Research Service (http://www.ars.usda.gov/Services/docs.htm?docid=3527&page=2): It is a good review chapter from the book ''Photosynthesis: A Comprehensive Treatise'' edited by A. S. Raghavendra.

The Z-Scheme is the description of the electron transfer in oxygenic photosynthesis. The scheme and its description are presented at http://www.life.uiuc.edu/govindjee/textzsch.htm. [For the scheme itself, see http://www.life.uiuc.edu/govindjee/ZSchemeG.html].

''Introduction to Electron Transfer'' by R. M. Williams of the Universiteit van Amsterdam (http://home.uva.nl/r.m.williams/Introduction%20to%20ET-30.htm): It is an

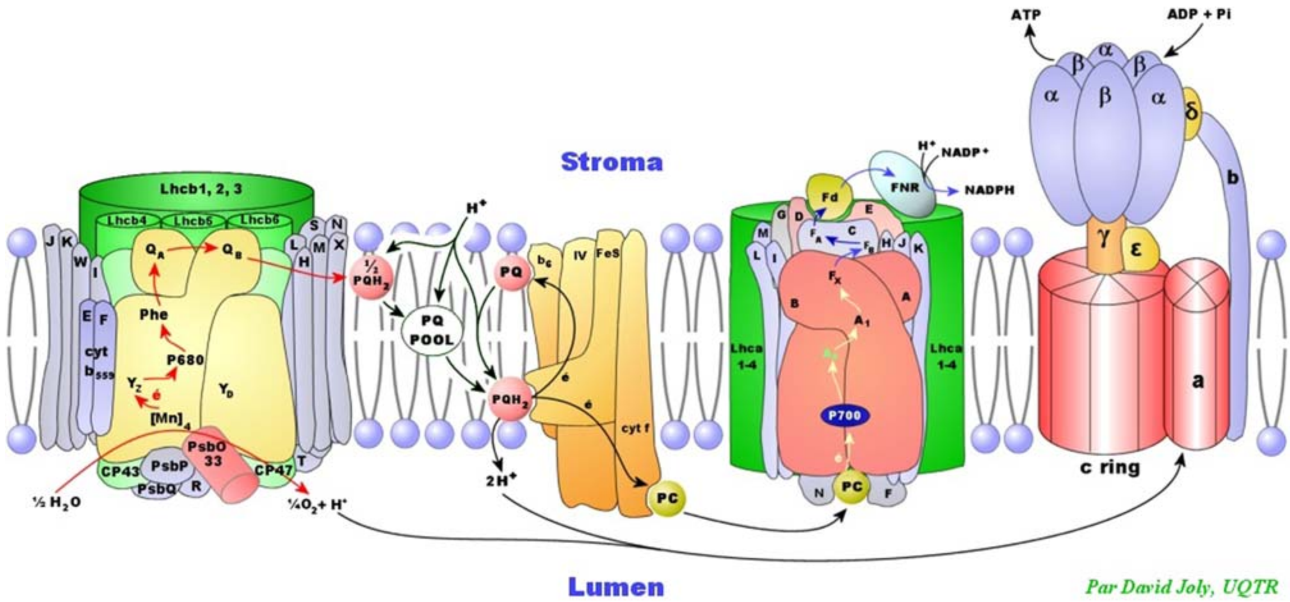

Fig. 6 Electron transfer in the Photosynthetic Membrane from Robert Carpentier's web site, http://www.uqtr.ca/labcarpentier/eng/home_frames.htm

excellent basic physico-chemical description of generalized electron transfer, and includes a very good exposure to the Rudolph Marcus theory and the equations.

''Electron Transfer in Hierarchical Photochemical Systems'' from Argonne National Laboratory (http://chemistry.anl.gov/photosynthesis/hierarchical_systems_Part2.html): It deals with bacterial as well as photosystem I reactions; use of EPR, among other methods.

Robert Carpentier's site at the Université du Québec à Trois-Rivières, http://www.uqtr.ca/labcarpentier/eng/home_frames.htm, uses frames that load very slowly, but it contains many excellent figures and is available in French and English (Fig. 6). The section on ''Photos'' contains many glimpses of photosynthesizers at various conferences.

Photosystems I and II

Carl Bauer's lab at Indiana University (http://www.bio.indiana.edu/~bauerlab/): The site contains nice descriptions and figures for photosystem gene regulation by oxygen and light. It also has information on the origin and evolution of bacterial photosynthesis.

''Crystal structure of Photosystem I at 2.5 Å resolution'' (Fig. 7) from the Institute for Crystallography at the Free University Berlin (http://userpage.chemie.fu-berlin.de/saenger/projects/ps1.html) and also, from the same site, ''First x-ray crystallographic model of water oxidising photosystem II'' (http://userpage.chemie.fu-berlin.de/saenger/projects/ps2.html). Highly recommended.

''Plastocyanin and Photosystem I. Ru-Modification'' by Örjan Hansson of Göteborg University, Sweden (http://www.bcbp.gu.se/~orjan/res/pc-ps1-e.html): It deals mainly with plastocyanin; it has references of the authors.

''Shedding New Light on the Earth's Powerstation'' from NASA describes the crystallizing of PS I on the space shuttle (http://www.science.nasa.gov/newhome/headlines/msad27jul98_1.htm) and (http://science.nasa.gov/newhome/headlines/msad10may99_1.htm): It is a technical achievement. A second group of PS I crystallization experiments was destroyed in the re-entry crash of the space shuttle Columbia (http://www.asu.edu/news/faculty_students/shuttle_020703.htm).

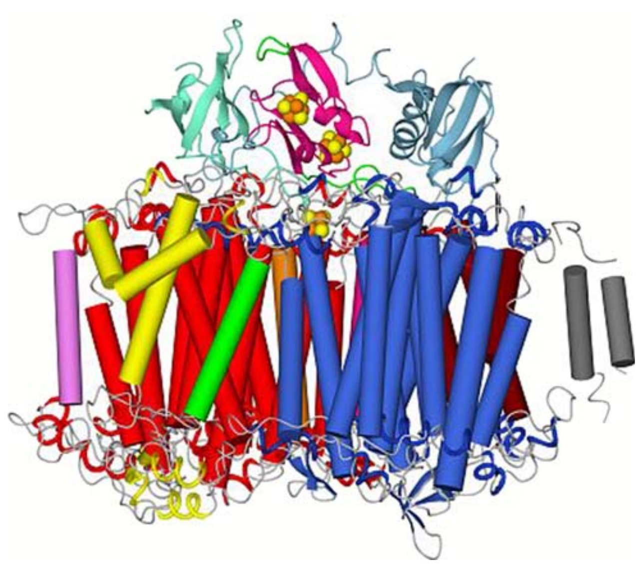

Fig. 7 The structure of Photosystem I from the Institute of Crystallography at the Free University Berlin, http://userpage.chemie.fu-berlin.de/saenger/projects/ps1.html

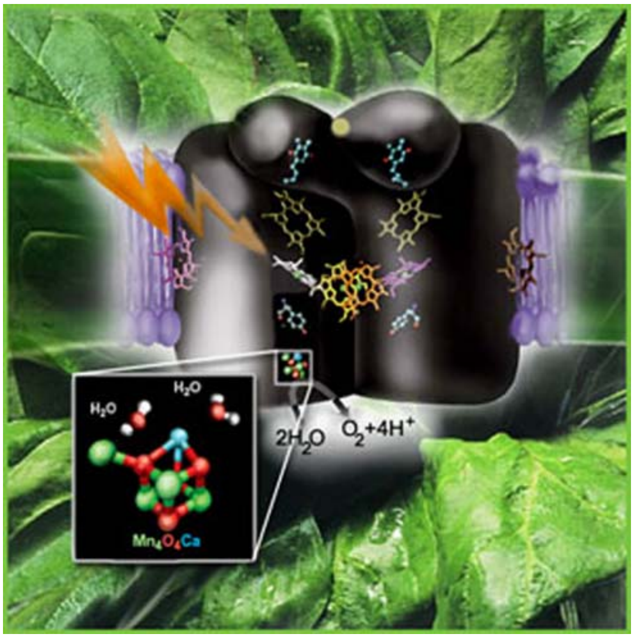

Fig. 8 The oxygen-evolving complex from ''Science Beat,'' a publication of the Berkeley Lab, http://www.lbl.gov/Science-Articles/Archive/sb/July-2004/2_spinach.html

Both ''Photosystem II'' (http://life.uiuc.edu/~a-crofts/psiiwork.html) and ''Structure and Function in Photosystem II'' (http://life.uiuc.edu/~a-crofts/psiistrc.html) from Antony Crofts are good sites to learn about Photosystem II. There is some overlap in the two sites.

''Photosystems I + II'' from James Barber at the Imperial College, London (http://www.bio.ic.ac.uk/research/barber/index.htm) shows work being done and the two photosystems in the Barber lab.

''Spinach, Or The Search For The Secret Of Life As We Know It'' (http://www.lbl.gov/Science-Articles/Archive/sb/July-2004/2_spinach.html) is a nicely illustrated article in ''Science Beat'' from the Berkeley Lab that discusses the evolution of the oxygen-evolving complex (Fig. 8).

Cytochromes and cytochrome oxidase

''Cytochromes'' from Scripps (http://metallo.scripps.edu/promise/CYTOCHROMES.html): The site contains chemical structures and descriptions of most of the cytochromes. This site is temporarily hosted by Scripps and may move in the future.

''Models for Cytochrome c Biogenesis'' from Washington University at St. Louis (http://www.biology.wustl.edu/faculty/models.html): It discusses three different systems for the biogenesis of cytochromes *c*.

''Cytochrome c Oxidase'' from the Theoretical and Computational Biophysics Group at the University of Illinois at Urbana (http://www.ks.uiuc.edu/Research/bio_ener/cco/): There is a basic description, and there are some key references.

''Cytochrome *c* Oxidase'' from Scripps (http://metallo.scripps.edu/promise/COX.html): It contains chemical structures; a good description; and bibliography.

''The bc_1-Complex Site'' from Antony Crofts at the University of Illinois at Urbana (http://www.life.uiuc.edu/crofts/bc-complex_site/index.html) and Ed Berry's Cyt bc page (http://sb20.lbl.gov/cytbc1/): These sites contain the structure obtained by Ed Berry's group; Crofts' page has links to coordinate data files of structures including that from J. Deisenhofer's group.

''Structure-Function Studies of the Cytochrome b_6f Complex'' from William Cramer at Purdue University (http://www.bio.purdue.edu/people/faculty/cramer/Cramer/html/cytbf.html): Here, you will find an excellent description of this complex (Fig. 9).

ATP synthase

''ATP Synthase'' by John Walker, the work that won him the Nobel Prize (http://www.mrc-dunn.cam.ac.uk/research/atp_synthase/): It is a beautiful site with many excellent illustrations and an incredible animation of the ATP synthase (http://www.mrc-dunn.cam.ac.uk/research/atp_synthase/rotarymech.php) and breakdown of the subunits (http://www.mrc-dunn.cam.ac.uk/research/atp_synthase/subunit.php) (Fig. 10).

''Animation Movies of ATP Synthase'' by Hongyun Wang and George Oster of University of California, Berkeley (http://nature.berkeley.edu/~hongwang/Project/ATP_synthase/) are great fun. Enjoy the site and learn from it. Plug-ins are required to view the animations.

''ATP Synthase,'' from Antony Crofts at the University of Illinois at Urbana, includes description and crystal structure (http://www.life.uiuc.edu/crofts/bioph354/lect10.html).

''The Photosynthetic ATP Synthase: Assembly of Hybrid Complexes from Bacterial and Plant Subunits Defines Their Roles in Catalysis'' by Zippora Gromet-Elhanan at the Weizmann Institute of Science (http://www.weizmann.ac.il/Biological_Chemistry/scientist/Elhanan/elhanan.html): It contains results from her research.

''ATP Synthase Sites for Biochemistry'' by Sandra L. Jewett, contains many good links (http://www.csun.edu/~hcchm001/wwwatp2.htm). It is a site that links to several sites containing information on Paul Boyer's binding change hypothesis; movies of the ATP Synthase. It is highly recommended by the authors.

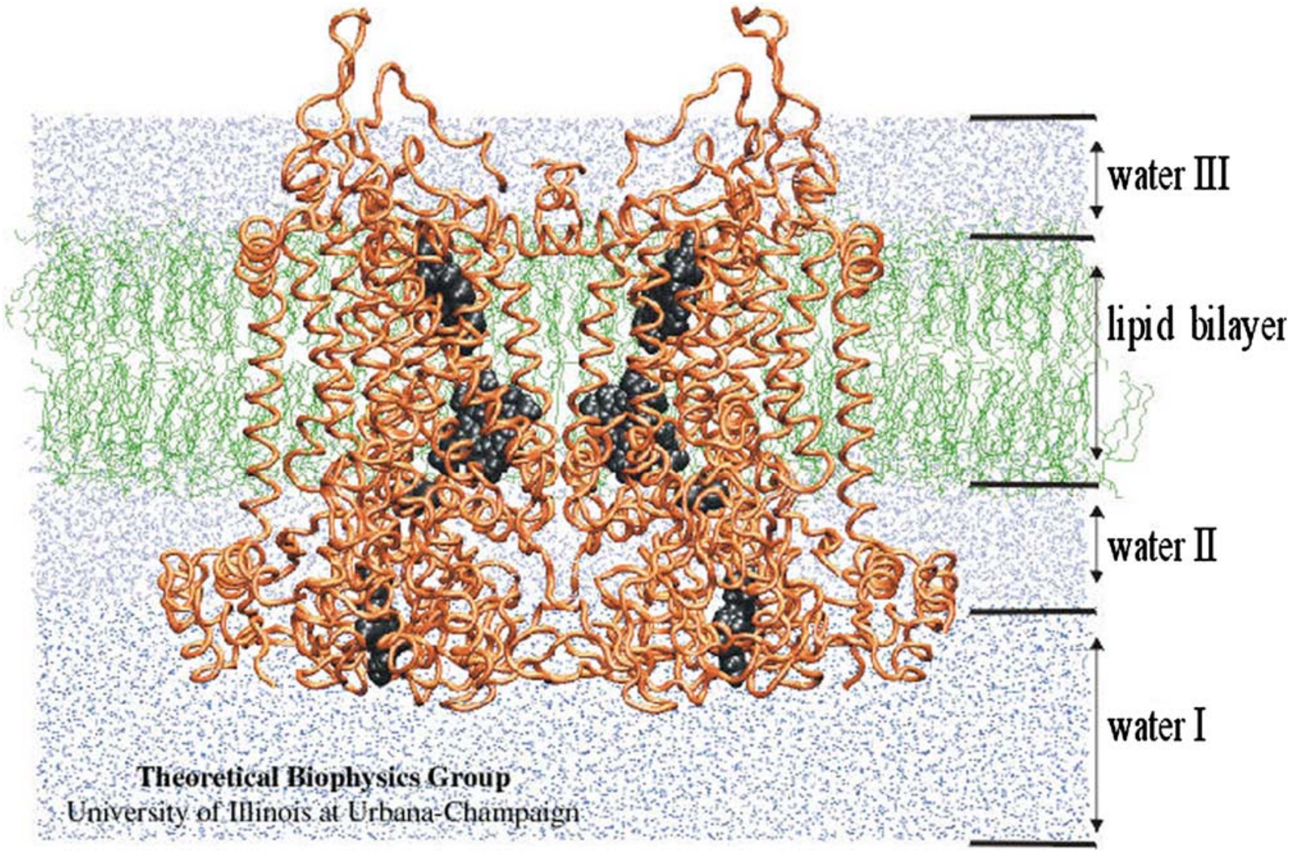

Fig. 9 ''Cytochrome bc1 complex'' (http://www.ks.uiuc.edu/Research/smd_imd/bc1/) from the Theoretical and Computational Biophysics Group at UIUC, http://www.ks.uiuc.edu/Research/smd_imd/bc1/

''Chloroplast ATP synthase: a molecular motor driving ATP synthesis'' (http://www.bio.indiana.edu/~hangarter-lab/courses/b373/lecturenotes/photosyn/atprotate.html) shows the rotation of the ATP synthase and includes figures from the original work by Hiroyuki Noji, Ryohei Yasuda, Masasuke Yoshida & Kazuhiko Kinoshita Jr.

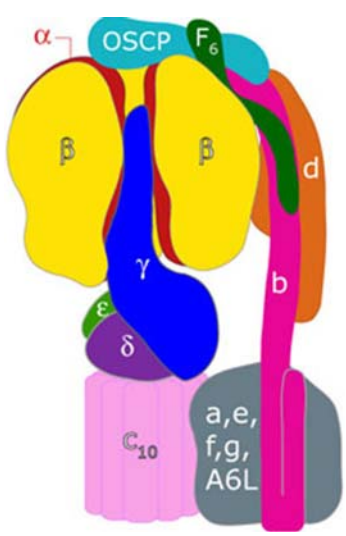

Fig. 10 Arrangement of subunits in mitochondrial ATP synthase, from John Walker's web site, http://www.mrc-dunn.cam.ac.uk/research/atp_synthase/subunit.php

C-3, C-4, and CAM (Crasulacean Acid Metabolism) pathways

''C3, C4, and CAM, Regulation of the Activity of Photosynthesis'' from Botany Online at the University of Hamburg (http://www.biologie.uni-hamburg.de/b-online/e24/24b.htm) includes useful information.

''How Plants Cope with the Desert Climate,'' by Mark A. Dimmitt, Arizona-Sonoran Desert Museum (http://www.desertmuseum.org/programs/succulents_adaptation.html): It is a basic general description of the CAM pathway written for the public. This wonderful site moves around frequently, so a search on its title might be required in the future.

The Princeton/Rutgers Environmental Science Institute has posted ''Global Warming Influences on C3 and C4 Photosynthesis'' which is a workshop on the subject and contains information of possible interest to teachers:

(http://www.woodrow.org/teachers/esi/1999/princeton/projects/c3_c4/).

Chlorophyll fluorescence

''Fundamentals of Chlorophyll Fluorescence'' from Optisci (http://www.optisci.com/cf.htm) is a good introduction to chlorophyll fluorescence from a commercial company. We wish more companies would post instructive information such as this, besides merely advertising their products.

''Using Chlorophyll Fluorescence to Study Photosynthesis'' from the Swiss Federal Institute of Technology, Zurich (ETH, Eidgenössische Technische Hochschule) (http://www.ab.ipw.agrl.ethz.ch/~yfracheb/flex.htm): It is a fairly good site with many figures and references for students.

''Fluorescence as a Probe of Biological Structure and Function'' from Govindjee at UIUC (http://www.life.uiuc.edu/govindjee/biochem494/biochem494a.html): You will find a bit of history; a basic description of Franck-Condon principle; basics of excitation energy transfer; some references; and a list of books. Date of site is, however, Spring, 1999.

Govindjee has also set up a page for the Kautsky Effect with a QuickTime movie showing the effect (http://www.life.uiuc.edu/govindjee/movkautsky.html). [A 3D presentation is available at http://www.greentech.cz/lapi/about/kautsky/index.html).]

''Chlorophyll fluorescence—a practical guide'' (http://jxb.oxfordjournals.org/cgi/content/full/51/345/659) is a well-written review article that is available to persons that belong to schools that subscribe to the online version of the *Journal of Experimental Botany*. Those, that cannot connect to this site, can download the free PDF version (http://jxb.oxfordjournals.org/cgi/reprint/51/345/659.pdf).

On the use of herbicides

''An introduction to herbicides'' (http://ipmworld.umn.edu/chapters/whitacreherb.htm): This site contains structures of many herbicides including Atrazine; Paraquat; Glyphosate, among others. There are also references.

''Herbicide Mode-Of-Action Summary'' by M.A. Ross and D.J. Childs of Crop Extension Service of Purdue University (http://www.ces.purdue.edu/extmedia/WS/WS-23-W.html) discusses the overall manner in which a herbicide affects a plant at the tissue or cellular level.

''Photosynthesis Inhibitors'' from the Sugarbeet Research & Education Board (http://www.sbreb.org/brochures/herbicide/photo.htm) discusses agricultural use of herbicides.

The chloroplast

''Virtual Cell'' is a journey into the workings of the chloroplast, from the Department of Plant Biology at UIUC (http://www.life.uiuc.edu/plantbio/cell/): This award-winning site by Matej Lexa is indeed a fun site. You can cut, zoom, turn, and really look at the ''inners'' of the chloroplast.

Wikipedia has a good article about chloroplasts (http://en.wikipedia.org/wiki/Chloroplast).

Claude W. dePamphilis at Penn State University maintains the Chloroplast Genome Database (http://chloroplast.cbio.psu.edu/) with links to information of interest to geneticists.

''Biological antennae also need to be tuned...'' (http://www.rhul.ac.uk/biological-sciences/AcademicStaff/Lopez-Juez/lopezlab.html) from Enrique Lopez-Juez at the University of London discusses how light and plastid signals regulate leaf and chloroplast development. There are many good photographs of Arabidopsis plants and chloroplast fluorescence and autofluorescence.

Biology 4Kids (http://www.biology4kids.com/files/cell_chloroplast.html) has easy to understand explanations and figures suitable for younger students.

FT Exploring is another site suitable for younger students (http://www.ftexploring.com/photosyn/chloroplast.html). It has good explanations, gives simple overviews and then much more detailed information for older students.

Pigments/carotenoids

''Photosynthetic Pigments'' from the University of California, Berkeley (http://www.ucmp.berkeley.edu/glossary/gloss3/pigments.html): It is a nice site discussing the three major pigments of plants, algae and cyanobacteria: chlorophylls; phycobilins; and carotenoids. The site also describes the characteristics of plants and cyanobacteria (there are nice pictures of cyanobacteria and suspensions of some algae).

The International Carotenoid Society (http://www.carotenoidsociety.org/) links to the chemical structures of many common carotenoids and articles, as well as its own newsletters.

The Carotenoids Page (http://dcb-carot.unibe.ch/carotint.htm) is a beautiful site presented by George Britton. It includes several pages on: Introduction, Occurrence, Structure, and Biosynthesis of Carotenoids, followed by a list of references.

The Wikipedia covers several aspects of carotenoids (http://en.wikipedia.org/wiki/Carotenoid).

''Nomenclature of Carotenoids'' (http://www.chem.qmul.ac.uk/iupac/carot/) has the very detailed IUPAC scientific rules for naming carotenoids. Although primarily useful only to specialists, it does give the public a taste for the complexities of naming chemical compounds.

''Photosynthetic Pigments'' (http://ghs.gresham.k12.or.us/science/ps/sci/soph/energy/photosyn/pigments.htm) site has a very simple explanation for K-12 students.

What if chlorophyll was not the primary pigment in plants? Two sites speculate on what plant life elsewhere might be like: ''Some Earth-like worlds may have foliage of colors other than green'' from a CalTech press release (http://mr.caltech.edu/media/Press_Releases/PR12971.html) and a related illustrated article from NASA, ''NASA predicts non-green plants on other planets'' (http://www.nasa.gov/centers/goddard/news/topstory/2007/spectrum_plants.html).

Rubisco (Ribulose bisphosphate carboxylase oxygenase)

''Rubisco: A First Look at the Mechanism'' from the School of Crystallography at Birbeck, University of London (http://www.scicom.demon.co.uk/Rubisco%20proj/Title_Page.html): It is a very good site that tells you what RUBISCO is; its mechanism of action; and provides many useful references.

''Ribulose-1,5-bisphosphate Carboxylase'' from University of Hamburg (http://www.biologie.uni-hamburg.de/lehre/bza/1rxo/e1rxoe.htm): The page opens with nice-colored pictures of the enzyme (Fig. 11). It discusses in depth the mechanism of action as well as the structure of the enzyme. It requires downloading plug-ins to view the animations.

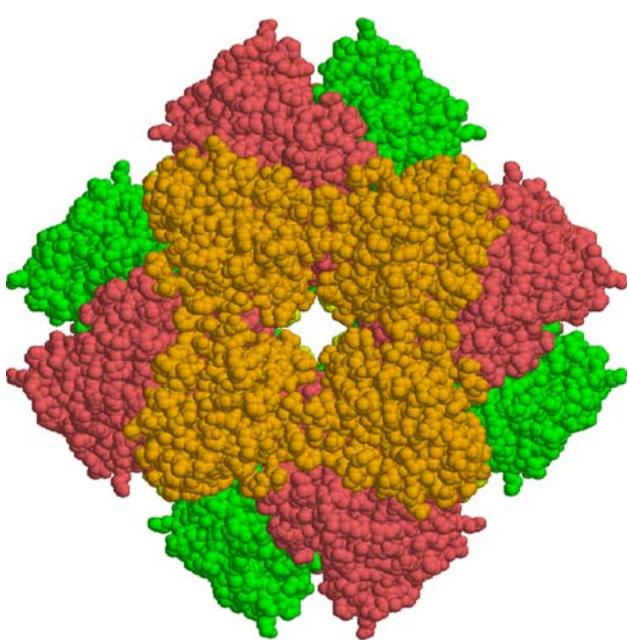

Fig. 11 Structure of Rubisco showing its four-fold symmetry. From the University of Hamburg site, http://www.biologie.uni-hamburg.de/lehre/bza/1rxo/e1rxoe.htm

Wikipedia has a very good article on Rubisco (http://en.wikipedia.org/wiki/RuBisCO).

The discovery of Rubisco is discussed in Vivienne Baillie Gerritsen's interesting article in Protein Spotlight, ''The Plant Kingdom's Sloth'' (http://www.expasy.org/spotlight/back_issues/sptlt038.shtml).

If you like humorous top ten lists, check out the ''I Love Rubisco'' site at (http://www.sabregirl.freeservers.com/rubisco.html). Our favorite is ''#8: Space filling models look kind of like Hortas—(Star Trek (We're almost as geeky as engineers)).''

Whole plant photosynthesis and plant stress

Free-Air CO_2 Enrichment Project (FACE) cooperative projects are being set up around the globe to study the impact of carbon dioxide on plants and crops growing in the open environment. A few sites of interest are: The Face Program (http://www.bnl.gov/face/faceProgram.asp); Australian Savanna FACE (http://www.cse.csiro.au/research/ras/ozface/index.htm); EuroFACE (http://www.unitus.it/euroface/); Oakridge: A FACE experiment in a deciduous forest (http://www.esd.ornl.gov/facilities/ORNL-FACE/). There are many more; the full list is at: http://cdiac.ornl.gov/programs/FACE/whereisface.html. SoyFACE (Soybean Free Air Concentration Enrichment) is an innovative facility in Urbana, Illinois, for growing crops under higher levels of carbon dioxide and ozone: (http://www.soyface.uiuc.edu).

''Field Photosynthesis Measurement Systems'' from New Mexico State University (http://weather.nmsu.edu/teaching_Material/soil698/Student_Material/Photosynthesis/): This site describes LICOR Gas exchange systems and their use for measuring whole plant photosynthesis.

''Plant Stress'' from Plantstress.Com (http://www.plantstress.com/): The site contains news from various sources that are related to plant stress.

''FIFE Canopy Photosynthesis Rates Data Set Guide Document'' is a technical report from Oak Ridge National Laboratory (http://www-eosdis.ornl.gov/FIFE/Datasets/Vegetation/Canopy_Photosynthesis_Rates.html). This site presents details of data on ''Canopy Photosynthesis'', collected in 1987 at several sites.

Bacterial (oxygenic and anoxygenic) photosynthesis

''Introduction to the Cyanobacteria'' from the University of California, Berkeley (http://www.ucmp.berkeley.edu/

bacteria/cyanointro.html): It shows two nice photographs of cyanobacteria and gives a short description. Follow the in-text links and you will be rewarded with a great deal of information on the history of cyanobacteria going back more than a billion years. It also includes information on pigments, how the bacteria changed the very atmosphere we breathe, and led to the existence of plants.

''Purple Non-Sulfur Photosynthetic Bacteria'' that supports the Bacteriology 102 course from the University of Wisconsin (http://www.splammo.net/bact102/102pnsb.html): It is a good teaching site at undergraduate level. It includes nice photos of bacterial cultures; description of bacteria and the media they are grown in.

''Energy Conversion by Photosynthetic Organisms'' from the Food and Agriculture Organization (FAO) of the United Nations (http://www.fao.org/docrep/w7241e/w7241e06.htm): The site provides some basic information on solar energy; plant and bacterial photosynthesis; and hydrogen production by photosynthetic organisms. There are references as well.

''Bacterial Photosynthesis'' (http://www.biologie.uni-hamburg.de/lehre/bza/photo/ebacphot.htm) from the University of Hamburg is very detailed and requires plug-ins.

Evolution of photosynthesis

''Origin of Microbial Life and Photosynthesis ''from Carl Bauer at Indiana University (http://www.bio.indiana.edu/~bauerlab/origin.html): The site has a clear text; beautiful evolutionary trees; and the photosynthetic gene cluster of heliobacteria.

''Evolution: When Did Photosynthesis Emerge on Earth?'' by David J. Des Marais at NASA Ames Research Center (http://edmall.gsfc.nasa.gov/aacps/news/Photosynthesis.html) and his article ''Evolution of Earth's Early Biosphere and Atmosphere'' (http://astrobiology.arc.nasa.gov/palebluedot/abstracts/ddm.html): The first text consists of extracts from a paper by Jin Xiong and coworkers, published in *Science* (Sep. 8, 2000).

''The Manganese-calcium oxide cluster of Photosystem II and its assimilation by the Cyanobacteria'' by James D. Johnson (http://www.chm.bris.ac.uk/motm/oec/motm.htm) discusses the evolution of the oxygen-evolving complex in cyanobacteria. It is very complete and contains many good illustrations and chemical structures.

''Geobiologists Solve ''Catch-22 Problem'' Concerning the Rise of Atmospheric Oxygen'' (http://pr.caltech.edu/media/Press_Releases/PR12927.html) is a news release from Caltech that discusses some puzzles about the early evolution of cyanobacteria and their ability to produce oxygen without poisoning themselves.

Photosynthesis and the environment/global climate change

''Greenhouse Gases and Society'' by Nick Hopwood and Jordan Cohen from the University of Michigan (http://www.umich.edu/~gs265/society/greenhouse.htm) covers many aspects including the Greenhouse Effect, greenhouse gases, effects on the environment and society. It has many good figures.

''The Decade After Tomorrow: Modeling Global Climate Change at Berkeley'' (http://sciencereview.berkeley.edu/articles.php?issue=7&article=greenhouse) by Kristen DeAnglis discusses work being done at UC-Berkeley. It is a good general article that discusses the problem and its complexities.

''Global Climate Change Policy Book'' (http://www.whitehouse.gov/news/releases/2002/02/climatechange.html) from the Bush White House describes his administration's plans for dealing with global climate change.

The U.S. Environmental Protection Agency (EPA) has a substantial website with many good links to discussions of the problem of global warming, climate policy, and useful hints as well as links to other resources (http://www.epa.gov/climatechange/).

Curious about the Kyoto Protocol? Here is the full text: http://unfccc.int/resource/docs/convkp/kpeng.html.

''Tropical Forests and the Greenhouse Effect: A Management Response'' by Norman Myers and Thomas J. Goreau (http://www.ciesin.org/docs/002-163/002-163.html): It is a 1991 paper; it has text and references, but no figures.

''Photoinhibition in Antarctic Phytoplankton by Ultraviolet-B Radiation in Relation to Column Ozone Values'' from the US National Science Foundation's (NSF) Office of Polar Programs (OPP) (http://www.nsf.gov/od/opp/antarct/ajus/nsf9828/9828html/j1.htm): It is a short article; has some references; and deals with ozone-related problems.

''Helping Ocean Algae Could Beat Greenhouse Effect'' by Bill Rosato describes how adding iron compounds to the water may help algae reproduce faster, thus removing more CO_2 from the atmosphere, (http://www.climateark.org/articles/2000/4th/heocalgc.htm). It is a 2-page news item.

''The Colors of Life'' from NASA (National Aeronautics and Space Administration, USA) demonstrates how satellites are tracking photosynthesis in the world's oceans to determine how well phytoplankton utilize carbon, http://www.gsfc.nasa.gov/gsfc/earth/pictures/2001/0327colors_of_life/carbon.htm.

''Photosynthesis, Trees, and the Greenhouse Effect'' is a lesson plan for teachers from the National Geographic (http://www.nationalgeographic.com/xpeditions/lessons/08/g68/brainpopphoto.html).

Rhodopseudomonas palustris (http://genome.jgi-psf.org/finished_microbes/rhopa/rhopa.home.html) is a bacterium with some interesting abilities that may be useful for our environmental future: it can sequester carbon dioxide and can produce hydrogen. A news release from the Ohio State University also discusses this useful bacterium (http://researchnews.osu.edu/archive/micromet.htm).

The EPA has a kid's site on the ''Greenhouse Effect'' (http://www.epa.gov/climatechange/kids/greenhouse.html) with simple explanations and links.

Artificial photosynthesis

''Mimicking Nature's Engine'' by Erik Ellis discusses some of the work of the ASU Center for the Study of Early Events in Photosynthesis (http://researchmag.asu.edu/stories/popeye.html). It is a news item with a short basic description.

The Swedish Consortium for Artificial Photosynthesis (http://www.fotomol.uu.se/Forskning/Biomimetics/consortium/index.shtm) discusses their research goals of using artificial photosynthesis to produce hydrogen.

''Artificial Photosynthesis'' by Michael Wasielewski group at Northwestern University (http://www.chem.northwestern.edu/~wasielew/res/ap.htm) discusses their work designing an artificial reaction center.

''Energy at the Speed of Light'' by Andrew Gathman at Penn State University (http://www.rps.psu.edu/0009/energy.html): It is a news item worth reading.

''Theory and Modeling of Biological Nanodevices'' by Klaus Schulten at the UIUC (http://www.foresight.org/Conferences/MNT8/Abstracts/Schulten/) contains a brief summary of using photosynthesis to develop nanodevices, an area of research that is pushing the envelope of photosynthesis research.

''Reinventing the Leaf'' by Philip Ball in Nature: Science Update (http://www.nature.com/nsu/991007/991007-3.html): It is a news item worth reading.

Bioenergy and photosynthesis

Steve Chu, the Nobel Prize laureate from Lawrence Berkeley lab writes about the promise of photosynthesis in ''Worldwide Energy Crunch: Power to the people – and how to keep it coming'' (http://www.sfgate.com/cgi-bin/article.cgi?f=/c/a/2005/07/17/EDGFVC9JA51.DTL&hw=Steve%2BChu&sn=001&sc=1000).

''Photosynthesis and Bioenergy'' (http://sols.asu.edu/grad/igels/photosynthesis.php) briefly describes new graduate programs at ASU that will tackle issues for the future. Stay tuned.

Oakridge National Laboratory has several programs to study bioenergy. A couple of interesting web pages have some Frequently Asked Questions (http://bioenergy.ornl.gov/faqs/index.html) and the bioenergy cycle (http://bioenergy.ornl.gov/papers/misc/bioenergy_cycle.html).

The newly established Center for Bioenergy and Photosynthesis at ASU contains numerous links to this new area of research (http://photoscience.la.asu.edu/photosyn/). The center is a large multidisciplinary group and incorporates the former ''ASU Center for the Study of Early Events in Photosynthesis.''

Individual researcher's sites

In this section we are listing a number of individual sites that we feel are quite well done. We favor sites that are created and maintained by the individuals themselves, not their departments, and which contain detailed research descriptions (not just brief summaries), useful figures, links to other sites, and personal information that help us see the researcher as a person. Many of the sites we have selected may seem a bit simple when first viewed, but their richness is revealed when links (sometimes very subtle due to the playful nature of scientists) are followed. Many more web sites will be found in the ''Nicelist'' web site maintained by one of us (LO) (http://photoscience.la.asu.edu/photosyn/nicelist.html). All sites are listed alphabetically by the researcher's last name. We apologize in advance to those we may have missed and will add new links to the online version as we discover them. Feel free to let us know of any amazing sites you create or run across.

John F. Allen (http://jfa.bio.qmul.ac.uk/~john/webstar/john/index.html). A deceptively simple site that contains quiet links to many areas of photosynthesis, as well as interesting private places. There are tours; there is animation; and there is music. John Allen was one of the very first photosynthesis researchers to have his own site.

James Barber (http://www.bio.ic.ac.uk/research/barber/index.htm). This site contains well-illustrated pages involving his research into Photosystem II, Photosystem I and other pages of interest.

Carl Bauer (http://www.bio.indiana.edu/~bauerlab/). Pages found here cover photosystem gene expression, evolution of photosynthesis, and more.

Robert E. Blankenship (http://biology4.wustl.edu/faculty/blankenship/). Interesting lab site with pages describing work on Photosystem I, chlorosomes, the Fenna-Mathews-Olson (FMO) protein, evolution of photosynthesis, and much more. Includes photos (http://biology4.wustl.edu/faculty/blankenship/images/AlvinTrip-Summer2000/index.html) from a dive in the Alvin submersible during which photosynthetic organisms were found living in the depths around volcanic vents! (http://

www.asu.edu/feature/includes/summer05/readmore/photosyn.html).

Donald Bryant (http://www.bmb.psu.edu/faculty/bryant/bryant.html) discusses research on structure and function and biogenesis of the photosynthetic apparatus of cyanobacteria and green sulfur bacteria, control of gene expression, and physiology. Most of the details and figures are found by clicking on the link to his lab web page.

John M. Cheeseman (http://www.life.uiuc.edu/cheeseman/main/). You know that a site that begins with, ''Purveyors of Versimilitude and Synthesizers of the Obvious since 1975,'' will be fun! Contains links to his research on mangroves, courses on form and function in higher plants, introduction to plant biology and field ecology. A software program (that you can download) for a multimedia textbook on photosynthesis (by Cheeseman and M. Lexa) is also available at (http://www.life.uiuc.edu/cheeseman/photosynthesis/main.html).

Richard J. Cogdell (http://www.gla.ac.uk:443/ibls/staff/staff.php?who=PPQled). Follow the links to a very rich web site with incredible images of light-harvesting complex II and the reaction centers.

William Cramer (http://www.bio.purdue.edu/people/faculty/cramer/Cramer/html/index3.html). Contains good descriptions and figures of work with the structure of cytochrome b6f complex, cytochrome f, and the Rieske iron-sulfur protein.

Antony Crofts (http://www.life.uiuc.edu/crofts/ahab/home.html). This site is a virtual goldmine of information. There is much here on the cytochrome bc1 complex and many other subjects, including many helpful links. It is great fun to watch the movement of the Rieske Iron sulfur protein.

Charles Dismukes (http://www.princeton.edu/~catalase/). A good site that contains many links to research on photosynthetic water splitting enzyme; manganese catalase; manganese cubane; and paleobiochemistry; it has good figures and discussions.

Graham Fleming (http://www.cchem.berkeley.edu/grfgrp/) contains information on the use of femtosecond spectroscopy to study light-harvesting photosynthetic compounds and many fun photos. The group photo is intriguing, especially the armed mob at the far right. Also check out his lab's work on quantum mechanical effects in photosynthesis (http://www.lbl.gov/Science-Articles/Archive/PBD-quantum-secrets.html) which may replace the classical energy transfer models.

Harry Frank (http://chemistry.uconn.edu/FrankGroup/frankg.html). This site contains several brief descriptions of work on the structure and function of carotenoids; role of xanthophylls in non-photochemical quenching of chlorophyll fluorescence; electrochemistry of cofactors of photosynthetic reaction centers. There are many fun things here and even a link to the Harry Frank podcast with the good professor on electric guitar [!] playing his song ''melted carrot'' (Fig. 12) as well as great discussion of carotenoids (http://chemistry.uconn.edu/FrankGroup/frank_podcast.html), and lots more. This is one of our favorite sites for its scientific as well as personal presentations.

Petra Fromm (http://www.public.asu.edu/~pfromme/index.html) uses crystallography to study the biophysical chemistry of membrane proteins. Much of her work can be found in links to PDF files.

Susan Golden (http://www.bio.tamu.edu/facmenu/faculty/sgolden.htm). There is information on the functional genomics of *Synechococcus elongatus*.

Govindjee (http://www.life.uiuc.edu/govindjee/). This site contains many links to all parts of the photosynthesis universe. There is a nice ''Photosynthesis Education'' site at http://www.life.uiuc.edu/govindjee/PSed_index.htm); slides made in 1998 on various aspects of photosynthesis starting at http://www.life.uiuc.edu/SpringGov/lectures/lecture04/slides through lecture07/slides Research publications in the areas of primary photochemistry; role of bicarbonate in Photosystem II; chlorophyll a fluorescence, among other topics can be found arranged according to journals and to topics. There are photographs of scientists and complete information on Volumes 19–25 of the Advances in Photosynthesis and Respiration.

Fig. 12 Harry Frank: photosynthetic musician, author of ''melted carrot,'' http://chemistry.uconn.edu/FrankGroup/frank_podcast.html

Arthur R. Grossman (http://carnegiedpb.stanford.edu/research/grossman2003_rev1/index.html). It begins with, ''There are oceans of biological questions and enigmatic organisms out there...'' and links to research involving cyanobacteria including some that live in hot springs.

Devens Gust (http://photoscience.la.asu.edu/photosyn/faculty/gust/index.htm). It has links to an article on 'Why Study Photosynthesis'; discussion of artificial photosynthesis including the making of proton gradients, and molecular electronics.

Roger Hangarter (http://www.bio.indiana.edu/~hangarterlab/). This site discusses environmental sensory response systems and plant development. It has Plants-in-Motion time-lapse movies; has information on Arabidopsis and links to Arabidopsis data bases; and has laboratory exercises for teaching plant growth and motion from elementary schools through college. Although not directly related to photosynthesis, it is a fun site. See for yourself. [Hint: check out the really weird Conehead saga at the Prymaat Files (http://www.bio.indiana.edu/~hangarterlab/otherstuff/prymatfiles/prymatmain.html)].

Alfred R. Holzwarth (http://www.mpi-muelheim.mpg.de/mpistr_holzwarth.html). Contains information on Photosystems I & II, antenna systems, and more.

Anastasio Melis (http://epmb.berkeley.edu/facPage/dispFP.php?I=25) studies green algae for photosynthetic production of hydrogen and hydrocarbon biofuels.

Sabeeha Merchant (http://www.chem.ucla.edu/dept/Faculty/merchant/index.html). This is a wonderful site on 'Biochemistry of Molecular Genetics and Metal Metabolism'; it has publication lists since her PhD days, but more importantly many of her papers on cytochromes and plastocyanin and a major review are available in PDF files. We find her 'Useful Links' very useful indeed. They include research resources; companies; composition (that has the famous ''The Elements of Style'' by William Strunk on line, loved by us); dictionaries; on-line journals; and genome data bases. There are also many, many photos of students, colleagues, and meetings.

Kenneth R. Miller (http://www.millerandlevine.com/km/index.html) from Brown University. Structure and function in biological membranes is the theme of research at this site. There is an interesting essay on ''Life's Grand Design'' (http://www.millerandlevine.com/km/evol/lgd/index.html); and a link to an interesting article in Discover on the perils and pitfalls of life with a Y chromosome (http://www.discover.com/issues/feb-95/departments/whitherthey470/). (Both of us needed to read it.) The site also contains information on beautiful biology text books by Miller and Joseph Levine. He has also become a well-known media supporter of evolution and critic of intelligent design and there is even a link to his appearance on the television show, the Colbert Report! (http://www.brown.edu/Courses/BI0020_Miller/talks/colbert-miller.mov).

Jon Nield at the Imperial College, London (http://www.bio.ic.ac.uk/research/nield/) has an incredibly rich site that covers the major protein complexes involved in photosynthesis. There are numerous discussions and incredible figures. For example, on his site you can click on any part of the complete structure (Fig. 13) (http://www.bio.ic.ac.uk/research/nield/psIIimages/oxygenicphotosynthmodel.html) and it will jump to a drawing of the individual complex with links to the various subunits. Wonderful.

James Norris (http://norrisgroup.uchicago.edu/index.html) conducts work on the photosynthetic reaction center. The links to his people are revealing and wacky.

Gunnar Öquist (http://www.upsc.se/index.php?option=com_content&task=view&id=2822&Itemid=43). His site discusses their research on ''Stress and Adaptation Mechanisms in Photosynthesis'' at Umeå University.

Donald Ort (http://www.life.uiuc.edu/ort/index.html). The site describes the strategies used by his laboratory on ''Molecular biochemical basis for environmental effects on photosynthesis and photosynthetic energy transduction.'' There is information on the possibilities of growing crops under future conditions of global change and links to his work at the USDA/ARS Photosynthesis Research Unit.

Kintake Sonoike (http://www.biol.s.u-tokyo.ac.jp/users/sonoike/lab-e.htm). The site contains some background on photosynthesis. The group studies 'Dynamics of photosynthesis under different types of stresses.' These include temperature, low CO_2, and rain. There is a colored cartoon of the four protein complexes of the thylakoid membrane.

F. Robert Tabita (http://www.osumicrobiology.org/faculty/ftabita.htm). Molecular regulation, biochemistry, and enzymology of carbon dioxide assimilation is the theme of research. You can study a conceptual model showing interplay of various factors involved in signal transduction and regulation of a gene. Further, structure predictions for archaeal RUBISCOs are shown.

Steve Theg (http://www-plb.ucdavis.edu/labs/theg/). The theme is transport of proteins across biological membranes and their assembly into larger multimeric complexes. Recent publications are listed in an elegant manner along with the photos of the cover pages of the journal; some are available as PDF files. An interesting text by Steve Theg is: ''Are you a cell biologist, a biochemist or a geneticist?'' (http://www-plb.ucdavis.edu/labs/theg/cartoon.htm). The site provides links to on-line journals; resources; data bases; software; and dictionary.

Elaine Tobin (http://www.mcdb.ucla.edu/Faculty/TOBIN/tobin.html). The theme here is phytochrome-regulated developmental processes, particularly of circadian clock in

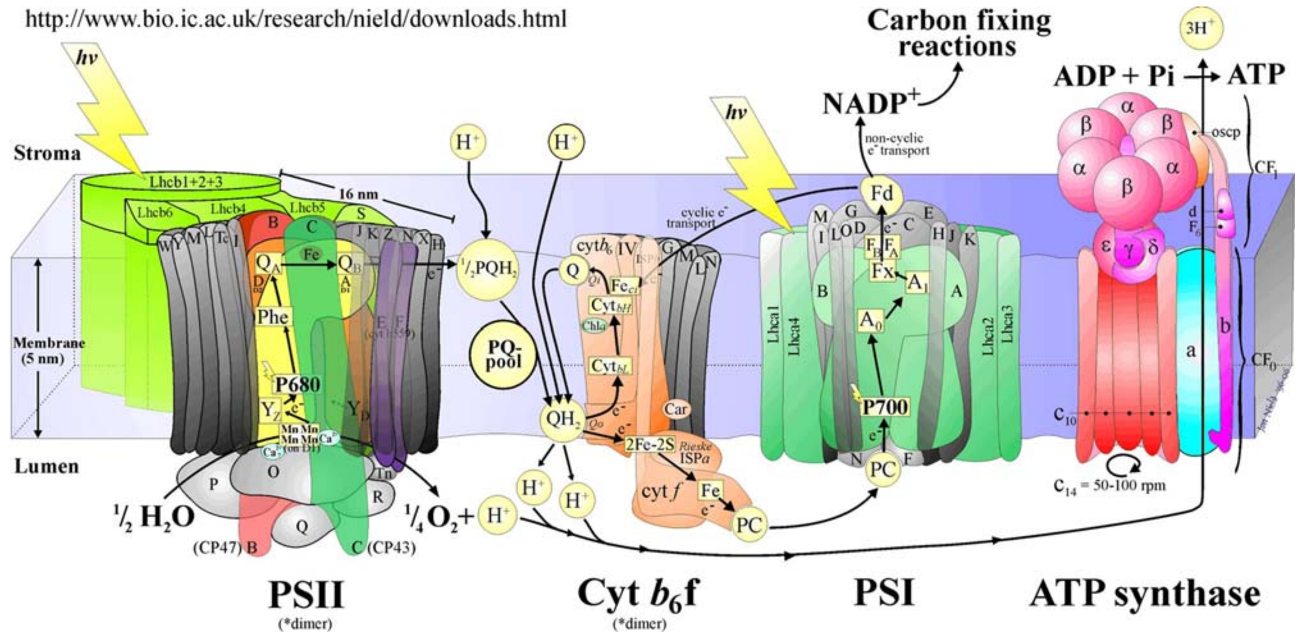

Fig. 13 The major protein structures from Jon Nield's site, http://www.bio.ic.ac.uk/research/nield/psIIimages/oxygenicphotosynthmodel.html

Arabidopsis. On the emotional side, you can see Philip Thornber's Memorial bench and its description by Alan Paulson (http://www.mcdb.ucla.edu/Research/Tobin/bench.html).

Wim F. J. Vermaas (http://photoscience.la.asu.edu/photosyn/faculty/vermaas.html). The theme is the molecular genetics of photosynthetic proteins. Wim studies structure, function, and assembly of photosynthetic proteins by genetic engineering. Recent publication list up to 1999 is available. Also, you can read ''An Introduction to Photosynthesis and its Application,'' published in World & I in 1998 (http://photoscience.la.asu.edu/photosyn/education/photointro.html). His link to one of the courses he teaches opens into his incredibly rich site on genetics and society.

Elizabeth Vierling (http://www.biochem.arizona.edu/vierling/). The theme is ''heat-shock proteins''; as molecular chaperones; during seed development; in *Arabidopsis*; and in *Synechocystis*. A list of publications organized by subject is also available.

David Alan Walker is a ''retired'' professor of photosynthesis who is producing some very interesting books and other items related to photosynthesis filled with humor and good illustrations (http://www.dawalker.staff.shef.ac.uk/daw/home/index.htm). His books appear in the section on ''Books'' later on in this paper. In August, 2004, he was presented The International Society of Photosynthesis Research's Communication Award (Fig. 14) for his outstanding efforts to help communicate information about photosynthesis to the general public.

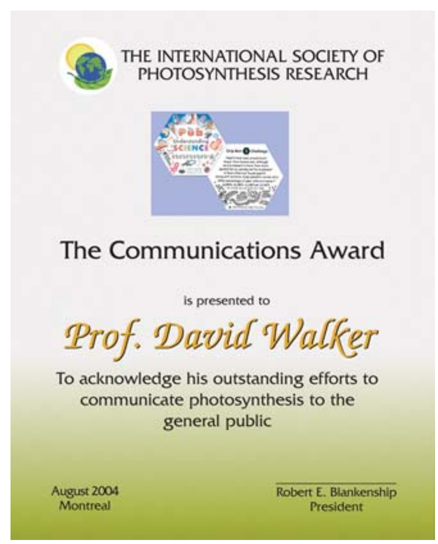

Fig. 14 David Walker's International Society of Photosynthesis Research's Communication Award for his outstanding efforts to help communicate information about photosynthesis to the general public, http://www.dawalker.staff.shef.ac.uk/daw/home/index.htm

Michael R. Wasielewski (http://www.chem.northwestern.edu/~wasielew/research.htm). There is good information and links here for photo-induced electron transfer, artificial photosynthesis, and molecular electronics, among others.

Neal Woodbury (http://www.public.asu.edu/~laserweb/woodbury/woodbury.htm). The theme is ''Molecular dynamics and mechanisms in protein mediated chemical reactions.''

Molecular level control of reaction mechanisms by protein structure is studied. Both antenna and reaction centers of photosynthetic bacteria are used. Ultrafast spectroscopy and hole burning methods are used.

Charles F. Yocum (http://www.biology.lsa.umich.edu/research/labs/cyocum/). The theme is biochemistry of photosystem II and oxygen evolution. The site has a complete lecture (with figures) entitled ''Light, Life and Photosynthesis: How Plants make Oxygen.'' You will find it at http://www.biology.lsa.umich.edu/research/labs/cyocum/files/lecture/CPROFLECT1.htm.

Educational sites for educators and students

Of course, all of the web sites discussed thus far can be used for educational purposes, but there are some which are primarily aimed toward students and educators. Also included is a list of sites that contain science experiments involving photosynthesis. Some books that may be useful are listed in the section on books and journals.

Educational sites

One of the best sites is the ASU Photosynthesis Center site. It contains an entire educational area for information about photosynthesis ranked by appropriate age groups (http://photoscience.la.asu.edu/photosyn/education/learn.html). This site is maintained by one of us (LO) and is revised frequently.

''Teaching Photosynthesis from the Internet'' is an ongoing project by one of us (G) to collect educational materials about photosynthesis in one easily accessed place (http://www.life.uiuc.edu/govindjee/photoweb/WWW-overview.html). It is very much like a condensed version of this entire paper and is organized by grade level.

Another project by one of the authors (G) lists photosynthesis educational links (http://www.life.uiuc.edu/govindjee/linksPSed.htm).

Flying Turtle.org has a very good page that explains photosynthesis in a creative and easily understood manner. The entire site is quite humorous and we recommend it highly (http://www.ftexploring.com/photosyn/photosynth.html).

Devens Gust at ASU has written an important essay, ''Why Study Photosynthesis,'' which instead of explaining the workings of photosynthesis, tells why it is so important to the world. He shows how students can use photosynthesis as a means to learn about many areas that may not seem to be linked to photosynthesis (http://photoscience.la.asu.edu/photosyn/study.html).

Newton's Apple, the show that originally appeared on Public Broadcasting Service (PBS) show has now moved to Twin Cities Public Television and has a good introduction to photosynthesis to young readers (http://www.newtonsapple.tv/TeacherGuide.php?id=915) and even the entire video from the original show (http://www.newtonsapple.tv/video.php?id=915).

John Cheeseman from UIUC is producing a line of educational software for the classroom (http://www.life.uiuc.edu/cheeseman/JC.software.html).

A sample from the ''National Science Education Standards'' regarding photosynthesis may be found at (http://www.nap.edu/readingroom/books/nses/html/photo6-e.html).

Science Made Simple, a service available by subscription has many items of interest to teachers, including the very popular ''Why Do Leaves Change Color in the Fall?'' which is available as a free sample on their web site (http://www.sciencemadesimple.com/leaves.html).

Leeward Community College and Kapi'olani Community College have a nice site for Oxidation/Reduction which is important to all life processes, not just photosynthesis (http://library.kcc.hawaii.edu/external/chemistry/). It also has a link to its section on photosynthesis equations (http://library.kcc.hawaii.edu/external/chemistry/everyday_photosyn.html).

Nelida Boreale provides a lesson plan for ''Photosynthesis and Transpiration'' for grades 5–8 (http://www.cbv.ns.ca/sstudies/science/sci1.html).

Lesson plans

''Electron Flow in Photosynthesis'' (http://www.zoo.utoronto.ca/able/volumes/vol-10/4-harris/4-harris.htm).

''Purification v. Population: Green v. Gray The Plant Kingdom's Impact on Air,'' by Maureen Taylor-French, Quality, Yale-New Haven Teachers Institute (http://www.yale.edu/ynhti/curriculum/units/2000/6/00.06.04.x.html).

''How Do Plants Get Energy?'' from Teacher's Domain and the television station WGBH (http://www.teachersdomain.org/resources/tdc02/sci/life/oate/lp_plantfood/index.html) contains links to NOVA movies and other resources. Free registration is required.

''Carbon: Is Too Much Of A Good Thing Bad?'' by George Y. Durrett (grades 6–8) (http://www.lpb.org/education/classroom/itv/envirotacklebox/nttifiles/6gdCarbon.html).

''Do Plants Need Sunlight?'' from Reach Out, (grades 1–6) (http://www.reachoutmichigan.org/funexperiments/agesubject/lessons/sunlight.html).

Experiments on the Web

There are many web sites detailing experiments that can be carried out in the classroom to show various aspects of photosynthesis. Some of the sites offer very simple experiments, while others are somewhat more involved.

The Russian space station Mir may be gone, but NASA has posted ‘‘Activity #1 Shuttle/Mir Seed Germination Activity’’ that explores hydroponics, photosynthesis, and seed germination (http://quest.arc.nasa.gov/smore/teachers/act1.html) which duplicates some of the experiments done on Mir.

Richard G. Steane has a number of experiments involving starch and Geraniums at the web site for ‘‘Experiments to Show the Factors Required in Photosynthesis (2) – Light and Carbon Dioxide’’ (http://www.biotopics.co.uk/plants/psfac2.html). The same site has a section with experiments on ‘‘Chlorophyll’’ in the plant Zebrina (http://www.biotopics.co.uk/plants/psfac1.html).

C. Ford Morishita has a web site involving starch pictures on leaves, ‘‘Photosynthetic Pictures Are Worth More Than a Thousand Words’’ (http://www.accessexcellence.org/AE/AEC/AEF/1996/morishita_pictures.html).

Nelida Boreale has developed a lesson plan involving a simple experiment for ‘‘Photosynthesis and Transpiration’’ (http://askeric.org/cgi-bin/printlessons.cgi/Virtual/Lessons/Science/Botany/BOT0046.html).

The Science and Plants for Schools (SAPS) organization has a site on ‘‘The response of leaf discs from sun and shade plants to green light’’ (http://www-saps.plantsci.cam.ac.uk/worksheets/scotland/sunshade.htm). SAPS also has a site for ‘‘Photosynthesis... using algae wrapped in jelly balls’’ (http://www-saps.plantsci. cam.ac.uk/worksheets/ssheets/ssheet23.htm). It also provides instructions for ordering a ‘‘Photosynthesis Kit’’ (http://www-saps.plantsci.cam. ac.uk/workshop_photo.htm).

A high-school level lab on ‘‘Photosynthesis, Respiration, and the ATP-ADP Cycle’’ has been written by Clovis O. Price Jr. (http://www.iit.edu/~smile/bi9614.html) in which beans are used to represent the various atoms involved in the photosynthesis process and are pasted on posters. Models will also be made using carved sponges. Finally, students will use tennis balls to demonstrate the ATP–ADP cycle.

Access Excellence has a couple of interesting experiments using Elodea and other organisms. James Linhares offers ‘‘A Constructivist Version of the Snail & Elodea Lab,’’ (http://www.accessexcellence.com/AE/AEC/AEF/1996/linhares_lab.html). A similar lab has been written by Bob Culler, ‘‘Mussel Your Way Through Photosynthesis,’’ which uses zebra mussels and Elodea in a project suitable for grades 9 and 10 (http://www.accessexcellence.com/AE/AEC/AEF/1995/culler_photo.html).

There are several other sites with lab experiments that use the common aquarium plant Elodea. Although the procedures are very similar, the lessons are written with slightly different perspectives and age groups in mind. Michael Gregory at SUNY (State University of New York)-Clinton (http://faculty.clintoncc.suny.edu/faculty/Michael.Gregory/files/Bio%20101/Bio%20101%20Laboratory/Photosynthesis/Photosynthesis.htm) has experiments using Elodea to show photosynthesis using pH probes and chromatography. These experiments are intended for a school lab and cannot be done at home due to the equipment and solvents used. A lesson has been written by Karen F. Adams of Burnside Scholastic Academy in Chicago (http://www.iit.edu/~smile/bi9201.html); it involves counting bubbles of gas given off by Elodea. Another lab on Light Intensity and Photosynthesis (http://www.geocities.com/CapeCanaveral/Hall/1410/lab-B-04.html) measures pH using pH papers and is a simple enough for small classrooms or even home use.

‘‘Photosynthesis and Chromatography of Its Pigments’’ (http://www.science-projects.com/PhotosynthPigments.htm) is a relatively simple experiment involving paper chromatography.

Neal Woodbury from ASU has set up a ‘‘Virtual Experiment’’ which uses mutant bacteria to discover which proteins are necessary for photosynthesis (Fig. 15). A virtual experiment is one in which the student follows a lab procedure on the computer screen rather than in a wet lab. Just like in the lab, the student has to correctly perform the

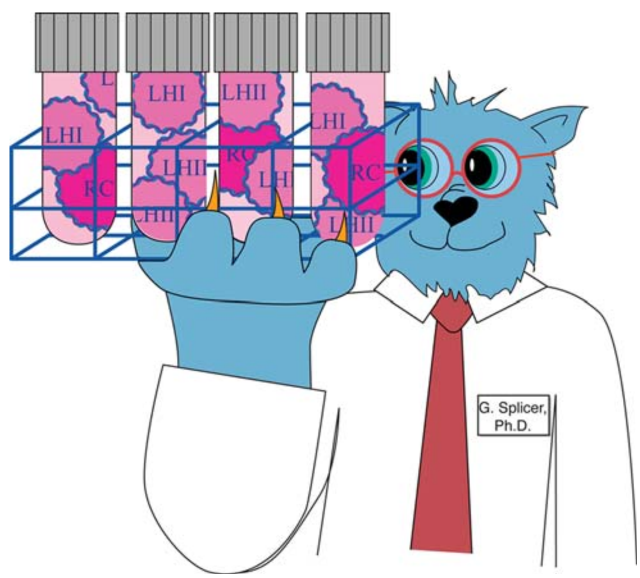

Fig. 15 Dr. Splicer prepares a virtual experiment at http://photoscience.la.asu.edu/photosyn/education/experiments/protein_exp/cover.htm

parts of the experiment or it fails (http://photoscience.la.asu.edu/photosyn/education/experiments/protein_exp/cover.htm).

Another virtual web lab for ''Elodea Photosynthesis'' (http://oldmanhonda.com/Biology/WebLabs/Elodea/Elodea.html) allows students to perform a timed lab with temperature and $NaHCO_3$ amounts. It is pretty neat, though sometimes slow, and requires that very specific instructions be followed—just like real science experiments.

Mike Adams at the Chlamydomonas Teaching Center has posted several experiments suitable for science fair projects (http://149.152.32.229/~mikeadams/).

Inexpensive kits that contain the algae required for the experiments can be purchased from Duke University via the Chlamydomonas Center (http://www.chlamy.org/strains/projects.html).

Other useful sites

Books and Journals

Although books about photosynthesis have not been placed online for economic reasons, there are web sites that discuss them and commercial sites that sell them. Some of those sites will be listed here. Many of them will include reviews or summaries and list the table of contents and some may even provide a sample chapter. Many journals are now becoming available online, but usually only to University libraries that pay for the service. Many Universities have discovered that it is cost effective (cheaper) to subscribe to the online journals on behalf of their students and faculty, than it is to try and subscribe to the hard copy versions of the journal which must be cataloged and archived by library personnel and is only available to one person at a time. Occasionally a hard copy of the journal is unavailable due to misfiling or because it has been sent out to be bound with other issues. The online version is always available and to as many persons as the library has paid for. Even if the journal issue is not available, the journal publisher's website will often contain the table of contents, abstracts, instructions to authors, and sometimes sample issues or articles. Some authors have also maintained certain rights to the papers or chapters they write allowing them to include them on their personal web pages. These can often be found by looking for an author's web site and then going to their publication lists. If their paper or chapter is available it will show up as a link.

Books

The most current set of books on photosynthesis and related matters is the *Advances in Photosynthesis and Respiration* series being published by Springer, with one of us (G) serving as its Series Editor (Fig. 16). Descriptions and ordering information can be found at three sites: the pub-

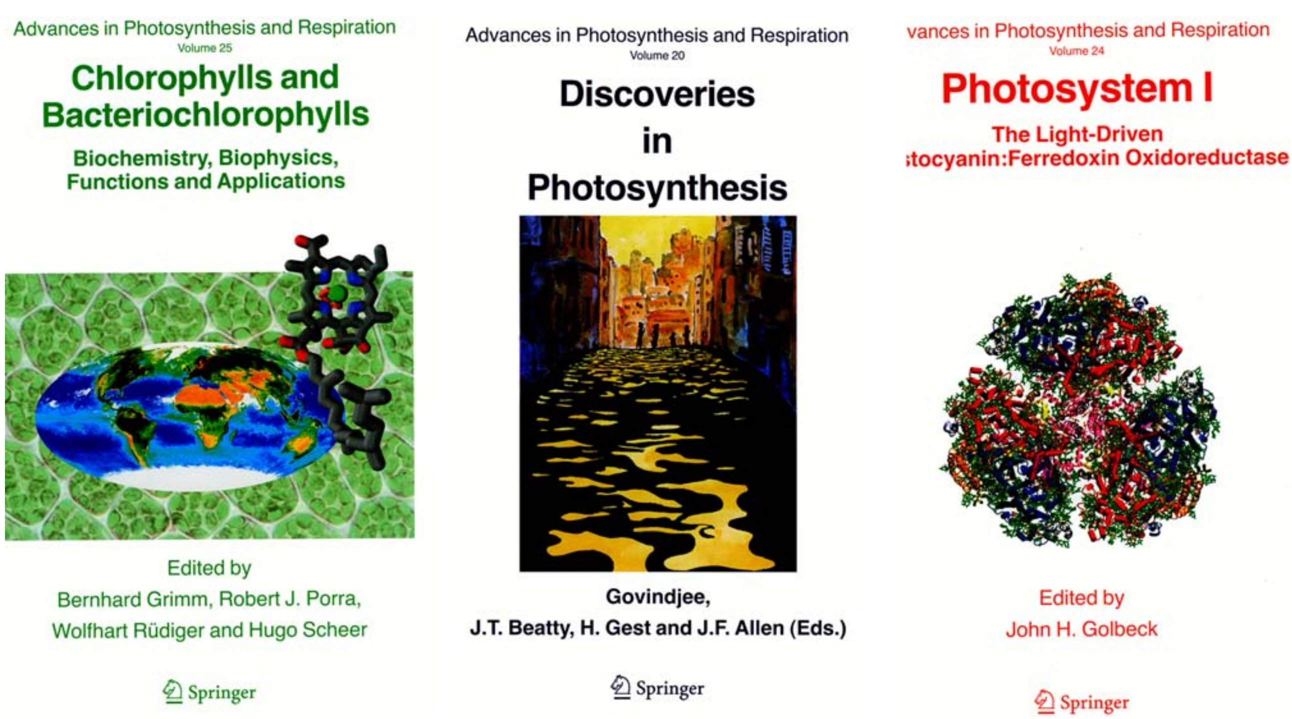

Fig. 16 Three books from the series ''Advances in Photosynthesis and Respiration.'' (Series Editor, Govindjee)

lisher (http://www.springer.com/west/home/life+sci?SGWID=4-10027-69-173624465-0), and at http://photoscience.la.asu.edu/photosyn/books/advances.html (for volumes 1–18) and (http://www.life.uiuc.edu/govindjee/newbook/Vol19–25.html) for volumes 19–latest. This series currently contains 25 volumes with more in press and in preparation:

The Molecular Biology of Cyanobacteria—edited by Donald A. Bryant

Anoxygenic Photosynthetic Bacteria—edited by Robert E. Blankenship, Michael T. Madigan, and Carl E. Bauer

Biophysical Techniques in Photosynthesis—edited by Jan Amesz and Arnold J. Hoff

Oxygenic Photosynthesis: The Light Reactions—edited by Donald R. Ort and Charles F. Yocum

Photosynthesis and the Environment—edited by Neil R. Baker

Lipids in Photosynthesis: Structure, Function and Genetics—edited by Paul André Siegenthaler and Norio Murata

The Molecular Biology of Chloroplasts and Mitochondria in Chlamydomonas—edited by Jean David Rochaix, Michel Goldschmidt-Clermont, and Sabeeha Merchant

The Photochemistry of Carotenoids—edited by Harry A. Frank, Andrew J. Young, George Britton, and Richard J. Cogdell

Photosynthesis: Physiology and Metabolism—edited by Richard C. Leegood, Thomas D. Sharkey, and Susanne von Caemmerer

Photosynthesis: Photobiochemistry and Photobiophysics—authored by Bacon Ke

Regulation of Photosynthesis—edited by Eva-Mari Aro and Bertil Andersson

Photosynthetic Nitrogen Assimilation and Associated Carbon and Respiratory Metabolism—edited by Christine Foyer and Graham Noctor

Light-Harvesting Antennas in Photosynthesis—edited by Beverley R. Green and William W. Parson

Photosynthesis in Algae—edited by Anthony W. D. Larkum, Susan E. Douglas, and John A. Raven

Respiration in Archaea and Bacteria: Diversity of Prokaryotic Electron Transport Carriers—edited by Davide Zannoni

Respiration in Archaea and Bacteria: Diversity of Prokaryotic Respiratory Systems—edited by Davide Zannoni

Plant Mitochondria: From Genome to Function—edited by David A. Day, A. Harvey Millar, and James Whelan

Plant Respiration: From Cell to Ecosystem—edited by Hans Lambers and Miquel Ribas-Carbo

Chlorophyll a Fluorescence: A Signature of Photosynthesis—edited by George C. Papageorgiou and Govindjee

Discoveries in Photosynthesis—edited by Govindjee, J. Thomas Beatty, Howard Gest, and John F. Allen

Photoprotection, Photoinhibition, Gene Regulation and Environment—edited by Barbara Demmig-Adams, William Adams III, and Autar K. Mattoo

Photosystem II: The Light-Induced Water:Plastoquinone Oxidoreductase—edited by Thomas J. Wydrzynski and Kimiyuki Satoh

Structure and Function of the Plastids—edited by Robert Wise and J. Kenneth Hoober

Photosystem I: The Light-Induced Plastocyanin:Ferredoxin Oxidoreductase—edited by John H. Golbeck

Chlorophylls and Bacteriochlorophylls: Biochemistry, Biophysics, Functions and Applications—edited by Bernhard Grimm, Robert Porra, Wolfhart Rüdiger, and Hugo Scheer

Biophysical Techniques in Photosynthesis II—edited by Thijs J. Aartsma and Jörg Matysik

Forthcoming:

The Purple Phototrophic Bacteria—edited by C. Neil Hunter, Fevzi Daldal, Marion C. Thurnauer, and J. Thomas Beatty

Other books of note are:

Aquatic Photosynthesis, 2nd Edition (2007), by Paul G. Falkowski (Brookhaven National Lab) and John Raven (University of Dundee). It is published by Princeton University Press. It has ten thorough chapters and eight nice colored plates. One of us (G) gives it high marks, ''It's a great book. It will be very useful for all biologists and oceanographers.'' It is available at Amazon.com (http://www.amazon.com).

Artificial Photosynthesis: From Basic Biology to Industrial Application, edited by Anthony F. Collings and Christa Critchley. It is available at Amazon.com (http://www.amazon.com).

C_3, C_4: Mechanisms and Cellular and Environmental Regulation of Photosynthesis, by Gerald Edwards and David Walker. A digital edition is available for free download from (http://www.oxygraphics.co.uk/c3c4.html). Also, Oxygraphics can still locate a few paper copies on your behalf.

Concepts in Photobiology: Photosynthesis and Photomorphogenesis, edited by Gauri S. Singhal, Gernot Renger, Sudhir K. Sopory, Klaus Dieter Irrgang, and Govindjee (https://www.vedamsbooks.com/no15011.htm)

Eating the Sun: How Plants Power the Planet, by Oliver Morton, published by Fourth State. One of us (G) has read the draft of several chapters in the book. The verdict is: it is a 'must' reading for all, even those only remotely interested in Photosynthesis. Available at http://www.amazon.com.

Energy Transduction in Biological Membranes. A Textbook of Bioenergetics, by William A. Cramer and David B. Knaff. See a book review at:

http://www.pubmedcentral.nih.gov/picrender.fcgi?artid=1275687&blobtype=pdf.

Membrane Biophysics, by H. Ti Tien and Angelica Ottova-Leitmannova (http://www.msu.edu/user/ottova/membrane.biophysics.html).

Molecular Mechanisms of Photosynthesis, by Robert E. Blankenship (https://www.blackwellpublishing.com/book.asp?ref=9780632043217&site=1). This is an excellent introduction to photosynthesis and is a great text for college-level courses. We recommend it to all our readers.

Molecular to Global Photosynthesis, edited by Mary D. Archer and James Barber. Available from Amazon.com (http://www.amazon.com).

Photobiology: The Science of Light and Life, 2nd Edition, edited by Lars Olof Björn has a clear and a thorough discussion on ''Light,'' its measurement and use in biology, including photosynthesis. See its website: http://www.springer.com/978-0-387-72654-0.

Photosynthesis, 6th Edition, by David O. Hall and Krishna K. Rao has gone through several editions and is still one of the best basic textbooks for the study of photosynthesis (http://www.cambridge.org/us/catalogue/catalogue.asp?isbn=9780521644976). Both the authors are now deceased. We hope that someone will take the challenge and produce an equally basic book.

Photosynthesis, 3rd Edition, by David Lawlor, is a good overall book. A reviewer wrote, ''This monograph gives a comprehensive overview of photosynthetic system.'' The book is available from Amazon.com (http://www.amazon.com).

Photosynthesis: A Comprehensive Treatise, edited by Agepati S. Raghavendra, is found at http://www.cambridge.org/us/catalogue/catalogue.asp?isbn=9780521570008 (1997, Cambridge Press). See also a review of this book by one of us (G) at http://www.life.uiuc.edu/govindjee/photoweb/4books.html.

Photosynthesis Research Protocols, edited by Robert Carpentier. It is available at Amazon.com (http://www.amazon.com).

Photosynthetic Excitons, by Herbert van Amerongen, Leonas Valkunas, and Rienk van Grondelle (http://www.worldscibooks.com/physics/3609.html).

Photosynthetic Unit and Photosystems-History of Research and Current Views (Relationship of Structure and Function), by A. Wild and R. Ball (http://www.euronet.nl/users/backhuys/phoun.htm) (1997, Buckuys Publishers). See also a review of this book by one of us (G) at http://www.life.uiuc.edu/govindjee/photoweb/4books.html.

Plant Biochemistry and Molecular Biology, by Hans-Walter Heldt (Institute of Plant Biochemistry, Göttingen) (with the collaboration of Fiona Heldt) is found at http://www.amazon.com/Plant-Biochemistry-Molecular-Biology-Hans-Walter/dp/019850179X (1997, Oxford University Press). See also a review of this book by one of us (G) at http://www.life.uiuc.edu/govindjee/photoweb/4books.html.

Probing Photosynthesis: Mechanism, Regulation & Adaptation, edited by Mohammad Yunus, Uday Pathre, and Prasanna Mohanty: (http://photoscience.la.asu.edu/photosyn/books/probebk.html).

David Walker has produced a wonderful set of books that approach photosynthesis from several different angles and which have been written for several age groups. Some have gone out of print but a few remaining copies on paper, and others as downloads or on CD-ROM, are available from (or via) Oxygraphics: http://www.oxygraphics.co.uk/ (be patient, some times it loads very slowly). Our favorites are: *A Leaf in Time* (for ages 8–12) which discusses photosynthesis and its relationship to energy, plants, and people (http://www.oxygraphics.co.uk/alit.html; also the first seven chapters of *A New Leaf in Time* (a much longer sequel in PDF format, for ages 9–99) is available for free download from http://www-saps.plantsci.cam.ac.uk/articles/broad_anlit.htm); *Energy, Plants and Man*, a large, profusely illustrated book with a great deal of information presented in an uncomplicated and humorous manner (http://photoscience.la.asu.edu/photosyn/books/walkerbk.html) is perfect for the classroom (high school, early college) or for just plain enjoyable reading (http://www.oxygraphics.co.uk/epm.htm); and *Like Clockwork* is a book in PDF format on a CD/ROM disk (Fig. 17). It covers the story of energy transduction in photosynthesis in an easily understood manner and contains many interesting links, including some surprises (http://www.oxygraphics.co.uk/bplc.html). All of these works are highly recommended. Should you encounter problems locating any of these books, feel free to email David Walker at <d.a.walker@sheffield.ac.uk> for availability.

Links to older volumes and books intended for young readers and the general public can be found at http://photoscience.la.asu.edu/photosyn/books.html. Also see http://www.life.uiuc.edu/govindjee/photoweb/2books.html for a list of single and two-authored books compiled by Govindjee. A list of other books edited by Govindjee is also available (http://www.life.uiuc.edu/govindjee/books.html).

An early classic 'Photosynthesis' by Eugene Rabinowitch and Govindjee, John Wiley (1969) is available free at: http://www.life.uiuc.edu/govindjee/photosynBook.html

Journals

Archives of Microbiology (http://link.springer.de/link/service/journals/00203/)

Functional Plant Biology (http://www.publish.csiro.au/?nid=102)

Fig. 17 Some of the great books written by David Walker, http://www.oxygraphics.co.uk/

Biochemistry (http://pubs.acs.org/journals/bichaw/index.html)

Biochimica et Biophysica Acta (BBA) (http://www.elsevier.com/wps/find/journaldescription.cws_home/506062/description#description)

Biomass & Bioenergy (http://www.elsevier.com/wps/find/journaldescription.cws_home/986/description#description)

Biophysical Journal (http://www.biophysj.org/)

Cell (http://www.cell.com/)

Environment, Development and Sustainability (http://www.environmental-expert.com/magazine/springer/envi/index.asp)

FEBS Letters (http://www.febsletters.org/)

Global Change Biology (http://www.blackwellpublishing.com/journal.asp?ref=1354-1013&site=1)

Global Environmental Change (http://www.elsevier.com/wps/find/journaldescription.cws_home/30425/description#description)

Journal of American Chemical Society (JACS) (http://pubs.acs.org/journals/jacsat/)

Journal of Biobased Materials and Bioenergy (http://www.aspbs.com/jbmbe.html)

Journal of Biological Chemistry (http://www.jbc.org/)

Journal of Computer-Aided Molecular Design (http://www.springer.com/west/home?SGWID=4-102-70-35677363-0&changeHeader=true&referer=www.wkap.nl&SHORTCUT=www.springer.com/prod/j/0920-654X)

Journal of Photochemistry and Photobiology B: Biology (JPP) (http://www.elsevier.com/wps/find/journaldescription.cws_home/504092/description#description)

Journal of Physical Chemistry (http://pubs.acs.org/journals/jpchax/index.html)

Nature (http://www.nature.com/nature/index.html)

Photochemistry and Photobiology (http://www.pol-us.net/PAPHome/)

Photosynthesis Research (http://www.springerlink.com/content/1573-5079/) the official journal of the International Society of Photosynthesis Research (ISPR) (http://www.photosynthesisresearch.org/).

Photosynthetica (http://www.ueb.cas.cz/ps/ps.htm)

Plant Molecular Biology (http://www.springerlink.com/content/1573-5028/)

Plant Physiology (http://www.plantphysiol.org/)

Proceedings of the National Academy of Sciences (USA) (http://www.pnas.org/)

Protein Science (http://www.proteinscience.org/)

Science (http://www.sciencemag.org/)

Societies and organizations

Some selected ones are listed below:

ISPR—International Society of Photosynthesis Research (http://www.photosynthesisresearch.org/) For only $50 (students and some others pay even less), you can become a member and get free online access to the international journal *Photosynthesis Research*, discounts on books and numerous other benefits. Further, ISPR members receive 25% discount on all books in the *Advances in Photosynthesis and Respiration* series published by Springer.

American Chemical Society: http://acswebcontent.acs.org/home.html

American Society for Horticultural Science: http://www.ashs.org/

ASP—American Society for Photobiology: http://www.pol-us.net/ASP_Home/index.html

ASPB—American Society of Plant Biologists [formerly American Society of Plant Physiologists (ASPP)]: http://www.aspb.org/

Biophysical Society: http://www.biophysics.org/

ESP—European Society for Photobiology (http://www.esp-photobiology.it/)

Inter-American Photochemical Society: http://www.i-aps.org/

International Carotenoid Society: http://www.carotenoidsociety.org/

Japanese Society of Plant Physiologists: http://www.jspp.org/eng/index.html

Phycological Society of America: http://www.psaalgae.org/

Databases and genome projects

The Arabidopsis Information Resource: TAIR (http://www.arabidopsis.org/index.jsp)

Chlamydomonas Center: http://www.chlamy.org/

Cyanosite: the Genome Database for Cyanobacteria: http://www-cyanosite.bio.purdue.edu/index.html

Rhodobacter sphaeroides genome project: http://www.rhodobacter.org/

Protein Data Bank (PDB): http://www.rcsb.org/pdb/home/home.do

Vendors and commercial suppliers

The following vendors that provide supplies, products, and equipment for photosynthesis research have requested that we list contacts to their sites.

Agrisera: http://www.agrisera.com/shop

Analytical Spectral Devices—field portable spectroradiometers: http://www.asdi.com/

Chemical Register: http://www.chemicalregister.com/

CID, Inc.—hand-held photosynthesis measuring systems: http://www.cid-inc.com/

DMP Ltd.— photosynthesis measuring systems: http://www.dmp.ch/control.php?&topgroupname=Environment

Dynamax: http://www.dynamax.com/

EARS—Environmental Analysis and Remote Sensing: http://www.ears.nl/

Fisher Scientific: http://www.fisher1.com/

Hansatech Instruments: http://www.hansatech-instruments.com/

Li-Cor Environmental Division: http://www.licor.com/env/

Olis—equipment for photosynthesis research: http://olisweb.com/

Opti-Sciences, Inc.—chlorophyll fluorometers: http://www.optisci.com/

Photon Systems Instruments—plant science, biotechnology, chlorophyll fluorescence, advanced images: http://www.psi.cz

PP Systems—photosynthesis, chorophyll fluorescence, spectrometers, environmental sensors: http://www.ppsystems.com/

Walz Company—instruments to measure gas exchange and chlorophyll fluorescence: http://www.walz.com/

References

Orr L, Govindjee (1999) Photosynthesis and the World Wide Web. In: Garab G (ed) Photosynthesis: mechanisms and effects, vol V. Kluwer Academic Publishers, Dordrecht, pp 4387–4392

Orr L, Govindjee (2001) Photosynthesis and the Web: 2001. Photosynth Res 68:1–28