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EDUCATIONAL REVIEW

Photosynthesis Web resources

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Abstract Online access to the Internet and the World Wide Web has become important for public awareness and for educating the world's population, including its political leaders, students, researchers, teachers, and ordinary citizens seeking information. After a brief Introduction, relevant information found on photosynthesis-related Web sites and other online locations is presented under five categories: (a) group sites, (b) sites by subject, (c) individual researcher's sites, (d) sites for educators and students, and (e) other useful sites.

Keywords Bioenergy · Climate change · Facebook · Internet · K-12 education · Social media · Solar fuel · Synthetic biology · Twitter · World Wide Web · YouTube

We dedicate this review to many "friends of photosynthesis" including Steven Brody (1927–2010, USA and Denmark), Rod Clayton (1922–2011, USA), Howard Gest (1922–2012, USA), Berger Mayne (1920–2011, USA), Mamoru Mimuro (1950–2011, Japan), Prasanna Mohanty (1934–2013, India), Gernot Renger (1938–2013, Germany), and David Walker (1928–2012, UK) for their highly significant contributions to photosynthesis research.

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Abbreviations

ASU	Arizona State University
FB	Facebook
HTML	Hyper Text Markup Language
ISPR	International Society of Photosynthesis Research
MOOC	Massive Open Online Course
NCSA	National Center for Supercomputing Applications
PDF	Portable Document Format
TED	Technology, Entertainment and Design
UIUC	University of Illinois at Urbana-Champaign
URL	Universal Resource Locator
WWW	World Wide Web

Introduction

The Internet and its collection of linked hypertext documents known as the World Wide Web (WWW or Web) have become very important resources for public awareness and for educating the world's population, including its political leaders, students, researchers, teachers, and ordinary citizens seeking information.

Only a few online sites were available when the first version of this paper appeared (Orr and Govindjee 1999) and finding information was difficult as search engines were still undergoing development. Concurrent with the rise of modern search engines, thousands of sites appeared, necessitating later revisions of this paper (Orr and Govindjee 2001, 2007). So much more happened in the following three years that yet a new version was necessary (Orr and Govindjee 2010). Audio presentations and lectures (podcasts) became very popular at universities. Videos featuring lectures and student presentations that were rare are now ubiquitous on YouTube and other providers. Some of the videos are superb and fantastic, though often ephemeral in nature. Now, this latest version of the review arises from the many changes that have occurred since 2010. Many of the older sites have vanished while new ones including online lessons and entire courses such as those presented by the Kahn Academy, TED (Technology, Entertainment and Design) Talks (hour long lectures) and TED Ed (brief lessons for younger students) have sprung up. Massive Open Online Courses (MOOC) have begun to appear at many universities and allow the public to sign up and take the courses on a non-credit basis, though some are now offering tests and certificates. It is too early to tell if these are the "next big thing" or just the latest fad. Social networking sites like Facebook and Twitter have become a quick way to disseminate breaking scientific news. One caveat when looking at social media sites is that most of these sites feature comment sections where users can post comments, some of which may be made by unknowledgeable persons and may not be appropriate or have anything to do with the topic.

This review presents relevant information on photosynthesis-related information grouped into several categories: (a) group sites, (b) sites by subject, (c) individual researcher's sites, (d) sites for educators and students, and (e) other useful sites. Because of 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 a good site, which is not mentioned in this article, we (larry.orr@asu.edu and gov@illinois.edu) would like to be informed so we can include it in our Web-based version of this review.]

As in our last edition, we would like to offer a brief literary quote to set the stage:

> Only when photosynthesis was invented, about two and a half billion years ago, did oxygen become part of earth's air and, because oxygen is a dangerous, reactive chemical, this poisoning of the planet wiped out many creatures and forced others into hiding. These oxygen-haters live to this day in lake bottoms, in swamps, and deep in the soil, eking out an existence in oxygen-free environments. Other creatures adapted to the new pollutant and, using an elegant sidestepping maneuver, turned the toxic oxygen to their advantage. Thus was born respiration using oxygen, an energy-liberating biochemical trick that we have inherited. Our lives therefore depend on an ancient form of pollution.—David George Haskell (2012) The Forest Unseen: A Year's Watch in Nature. Viking, pp. 26–27.

Group sites

The largest group site, the Arizona State University (ASU) Center for Bioenergy and Photosynthesis, went online in 1995. Formerly known as the Center for the Study of Early Events in Photosynthesis, the center expanded its areas of interest to emphasize bioenergy research into alternative fuels derived from photosynthetic bacterial biomass, the production of hydrogen from model systems influenced by photosynthesis, 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 changed its name. Its Web site was developed and is currently maintained by one of us (LO) and can be accessed at http://bioenergy.asu.edu. 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. Early on, the center site was tasked to cover "all things photosynthesis" and this has now expanded to include bioenergy matters and related issues such as climate change and other solar energy topics. 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://bioenergy.asu.edu/photosyn/education/learn.html). Recently, the center added Facebook (http://www.facebook.com/pages/Tempe-AZ/Center-for-Bioenergy-Photosynthesis/121720517379?ref=ts) and Twitter (http://twitter.com/bioenergycenter) pages in order to provide breaking news to the public. Another popular area is its 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://bioenergy.asu.edu/photosyn/nicelist.html). Some of the center's other Web pages will be mentioned in the other sections. An artistic representation of the promise of bioenergy from photosynthesis is shown in Fig. 1.

ASU is also the home of a Department of Energy Frontier Research Center (EFRC), the ASU Center for Bio-Inspired Solar Fuel Production (http://solarfuel.clas.asu.edu/), established in 2009. Closely affiliated with the Center for Bioenergy & Photosynthesis, this new center approaches the design of a complete system for solar water

Fig. 1 Artist's representation of the ASU Center for Bioenergy and Photosynthesis (http://bioenergy.asu.edu), showing energy from the sun powering a symbolic sustainable energy green mill. Artwork by Michael Hagelberg, used by permission

oxidation and hydrogen production by applying the fundamental design principles of photosynthesis to the construction of synthetic components, and their incorporation into an operational unit. The functional blueprint of photosynthesis is being followed, using non-biological materials. See below in the "Bioenergy/biofuels/solar fuel/biomass" section for more EFRC sites related to photosynthesis and renewable bioenergy research.

Also at ASU, the Polytechnic campus in Mesa is the home of the Arizona Center for Algae Technology and Innovation (AzCATI) (http://www.azcati.com/) and the Laboratory for Algae Research Biotechnology (LARB) (http://larb.asu.edu/), two groups researching various aspects of algal and cyanobacterial production of biofuels and byproducts.

The University of Illinois at Urbana-Champaign (UIUC), home of 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.illinois.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 that can be used in the classroom. A unique resource is the availability of some of Govindjee's older books as well as the classical book on Photosynthesis by Eugene Rabinowitch (source: "Biodiversity Heritage library" on the internet) (http://www.life.illinois.edu/govindjee/g/Books.html). A significant item is the availability of the complete references of all the chapters in Volumes 1–31 of Govindjee's Series 'Advances in Photosynthesis and Respiration' (Springer) (http://www.life.illinois.edu/govindjee/g/References.html); it also includes PDFs of the front matter of volumes 32–35. UIUC is also the home of the wonderful and highly educational site of A. R. Crofts (http://www.life.illinois.edu/crofts/ahab/index.html). The Photosynthesis Research Unit (http://www.ars.usda.gov/main/site_main.htm?modecode=36-11-35-00), 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/Gallery/Movies/) and much more.

The Photosynthesis Group at Queen Mary University of London, UK (http://queenmaryphotosynthesis.org/) 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. Also see the Web sites for John Allen and Jon Nield in the "Individual researcher's sites" section.

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. It is also the home of the new SOLAR-H program to bring together laboratories to do basic research on hydrogen production from renewable sources (http://www.fotomol.uu.se/Forskning/Biomimetics/solarh/index.shtm).

The Avron-Wilstätter Center for Photosynthesis Research is located at the Weizmann Institute of Science, Israel. (http://www.weizmann.ac.il/acadaff/Scientific_Activities/2009/wilstatter_center.html) and is working with several groups to study many areas of photosynthesis.

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.illinois.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://bioenergy.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).

The *Encyclopaedia Britannica* article on photosynthesis is available at: http://www.britannica.com/EBchecked/topic/458172/photosynthesis.

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, and lasers. A truly wonderful site!

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. (Interestingly, FT stands for "Flying Turtle," the mascot of this clever Web site.)

The American Society of Photobiology has posted "Basic Photosynthesis" by Thomas Brennan: http://www.photobiology.info/Brennan.htm, and "Systems Biology of Photosynthesis" by Xin-Guang Zhu: http://www.photobiology.info/Zhu.html.

Ted Ed presents an easily-understood animated overview of photosynthesis for younger students at "The simple story of photosynthesis and food—Amanda Ooten" (http://ed.ted.com/lessons/the-simple-but-fascinating-story-of-photosynthesis-and-food-amanda-ooten).

Specific subject sites

There are many sites that specialize in a certain aspect of photosynthesis. Here are some of the best arranged by topic. Many of the sites overlap somewhat and some may appear in more than one group, for example, the first three (Artificial Photosynthesis; Bioenergy/Biofuels/Solar Fuel; and Oxygen Evolution/Oxygen-Evolving Complex/Water splitting) are very closely related as all are currently popular areas of research using artificial photosynthesis techniques for much of their study.

Artificial photosynthesis

The Joint Center for Artificial Photosynthesis (JCAP) (http://solarfuelshub.org/index.html) is a DOE Energy Innovation Hub studying artificial solar-fuel generation. It is located at the California Institute of Technology and includes researchers from several major universities.

The Swedish Consortium for Artificial Photosynthesis (1994–2005) (http://www.fotomol.uu.se/Forskning/Biomimetics/consortium/index.shtm) discusses their research goals of using artificial photosynthesis to produce hydrogen.

The Michael Wasielewski group at Northwestern University (http://chemgroups.northwestern.edu/wasielewski/research_apsolarfuels.html) discusses their work designing an artificial reaction center.

MIT News presents "Capturing energy form the sun" (http://web.mit.edu/newsoffice/2013/capturing-energy-from-the-sun.html), an article about the work done there incorporating nanotubes that serves as light-harvesting antenna.

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

"Running on sun" (http://www.rsc.org/chemistryworld/2012/09/artificial-photosynthesis-sustainable-energy) from Chemistry World describes the efforts to create sustainable energy using artificial photosynthesis.

"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.

The Photovoltaic & Optoelectronic Devices group at Universitat Jaume I (UJI), Castellón de la Plana, Spain, is also working on a leaf-like device created using nanotechnology: "Artificial photosynthesis turns water into hydrogen" (http://optics.org/news/3/6/7).

"How Artificial Photosynthesis Works" from HowStuffWorks discusses several aspects of artificial photosynthesis in an easy-to-understand manner (http://science.howstuffworks.com/earth/green-technology/energy-production/artificial-photosynthesis.htm).

YouTube video "The Artificial Leaf" (http://www.YouTube.com/watch?v=c-s_c6HjDwM) is where Daniel Nocera discusses the possibilities in this award winning video by Jared P. Scott and Kelly Nyk (3:46 min).

YouTube video "Nocera Leaf" (http://www.YouTube.com/watch?v=ztdzTyVFtZg) is a clever video with animations that discusses the work of the Nocera lab.

Bioenergy/biofuels/solar fuel/biomass

Steve Chu, former Secretary of the US Department of Energy, and 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). Steve Chu also has a Facebook site for those that are interested, http://www.facebook.com/stevenchu.

"Renewable Biological Systems for Alternative Sustainable Energy Production" from the Food and Agriculture Organization of the United Nations (http://www.fao.org/docrep/w7241e/w7241e00.htm): The site provides a great deal of basic information with chapters on biological energy production from photosynthetic organisms.

The American Society of Photobiology has posted "Applied Photosynthesis for Biofuels Production" by Michael Seibert: http://www.photobiology.info/Seibert.html.

The Center for Bioenergy and Photosynthesis at Arizona State University (ASU) contains numerous links to this developing area of research (http://bioenergy.asu.edu). As mentioned above, the center is a large multidisciplinary group and incorporates the former "ASU Center for the Study of Early Events in Photosynthesis." The ASU Research Magazine has several articles about recent activities. "Catching some rays: Harnessing the power of photosynthesis" (http://researchstories.asu.edu/stories/catching-some-rays-harnessing-power-photosynthesis-945) discusses the history and evolution of photosynthesis and its potential to develop sustainable energy sources. "Bacteria for biofuel" (http://researchstories.asu.edu/stories/bacteria-biofuel-934) discusses current projects to develop biofuels from cyanobacteria. Producing hydrogen from microorganisms is the topic of "Bacteria and sunlight make clean, green hydrogen" (http://researchstories.asu.edu/stories/bacteria-and-sunlight-make-clean-green-hydrogen-844).

Arizona State University is also the home of the Laboratory for Algae Research and Biotechnology (LARB) (http://larb.asu.edu/) run by Milton Sommerfeld and Qiang Hu. See Fig. 2. Their site contains links to their research, grants and videos. There is also a good PDF file on biofuels (http://larb.asu.edu/files/biofuel_brochure.pdf). The researchers' work was listed as one the best inventions for 2008 in a Time magazine article (http://www.time.com/time/specials/packages/article/0,28804,1852747_1854195_1854150,00.html).

Sommerfeld and Hu also run the Arizona Center for Algae Technology and Innovation (AzCATI) (http://www.

Fig. 2 Cover of a brochure describing the work done by the Laboratory for Algae Research and Biotechnology (LARB) at ASU (http://larb.asu.edu/files/biofuel_brochure.pdf)

azcati.com/) that serves as a hub for research, testing, and commercialization of algae-based products. A Vimeo vido discussing their work on algal biofuels is available at http://vimeo.com/12119179.

A TED Talk by Jonathan Trent on "Energy from floating algae pods" is available at http://www.ted.com/talks/jonathan_trent_energy_from_floating_algae_pods.html.

Another TED Talk by Craig Venter discusses "DNA and the Sea" (http://www.ted.com/talks/craig_venter_on_dna_and_the_sea.html), showing the possibilities of using synthetic biology to engineer organisms in the hopes of creating alternative fuels.

Video from UIUC on the tall grass Miscanthus, which is a candidate for ethanol production, is at: http://news.illinois.edu/slideshows/Miscanthus_Yield/index.html.

Wikipedia has a good entry on "Biohydrogen reactors" at: http://en.wikipedia.org/wiki/Biological_hydrogen_production.

"Biomass" from the Department of Energy's Energy Kids site has a good explanation of biomass for K-12 students (http://www.eia.gov/kids/energy.cfm?page=biomass_home-basics).

The US Department of Energy (DoE) has funded a number of Energy Frontier Research Centers (EFRC) (http://science.energy.gov/bes/efrc/) related to photosynthesis and bioenergy. As part of the mandate from the DoE, these sites post progress reports as well as other important information.

Arizona State University is home to one of the EFRC centers, the Center for Bio-Inspired Solar Fuel Production (http://solarfuel.clas.asu.edu). The goal is to produce hydrogen or other solar fuels from sunlight utilizing artificial photosynthesis.

Washington University, St. Louis: Photosynthetic Antenna Research Center (PARC) http://parc.wustl.edu. They also have a Facebook site: https://www.facebook.com/WUParc?fref=ts.

University of Delaware: Center for Catalytic Science & Technology: http://www.che.udel.edu/ccst/.

Northwestern University: Argonne-Northwestern Solar Energy Research Center (ANSER): http://www.ansercenter.org/.

Purdue University: Center for Direct Catalytic Conversion of Biomass to Biofuels (C3Bio): http://www.purdue.edu/discoverypark/c3bio/index.php, plus they have a Twitter site: http://twitter.com/c3bio.

Donald Danforth Plant Science Center: Center for Advanced Biofuels Systems (CABS): http://www.danforthcenter.org/cabs/.

Penn State: Center for Lignocellulose structure and formation: http://www.lignocellulose.org/.

The University of North Carolina at Chapel Hill: Solar Fuels & Next Generation Photovoltaics: http://www.efrc.unc.edu/index.html. Artificial Photosynthesis is one of the areas of research for this new center.

The Arizona Solar Center (http://www.azsolarcenter.org/) contains a great wealth of information on solar energy activities in Arizona, including information for consumers and the general public.

Bruce Bare and Shulin Chen from the University of Washington Denman Forestry Institute present a video lecture on "Bioenergy and Biofuels: An Overview of Bioenergy and Biofuels Production" (http://www.YouTube.com/watch?NR=1&feature=endscreen&v=zm1z9vZ4K0k) (57:41 min).

Daniel Nocera and Angela Belcher discuss "The Role of New Technologies in a Sustainable Energy Economy," a long video lecture (1 h, 32 min) presented by MIT (http://video.mit.edu/watch/the-role-of-new-technologies-in-a-sustainable-energy-economy-9193/). In a second lecture in the MIT series, Nocera discusses "Personalized Energy," in which he discusses his opinions on a "solution to the energy challenge rests in providing the non-legacy (developing) world a carbon–neutral, sustainable energy supply" (http://video.mit.edu/watch/personalized-energy-9528/) (1 h, 37 min).

An interesting quote from the MIT Web page (http://web.mit.edu/newsoffice/2009/nocera-video.html) is:

> On advice he received from Kurt Vonnegut: He told me, 'stop worrying about the planet dying. When you have a big organism and you become irritating to it, the immunological system just kicks in and kills the invading organism'. And he assured me that we have just become so irritating to the earth, she'll just kill us. Which makes me happier. It says that there is something much bigger than us, which we forget about the earth. And she is much more powerful than us. She'll get rid of us if we don't take care of her.—Daniel Nocera.

Oxygen evolution/oxygen-evolving complex/water splitting

The Berkeley Lab at the Lawrence Berkeley National Laboratory has an updated article on "The Next Big Step Toward Atom-Specific Dynamical Chemistry" that discusses the oxygen-evolving complex (http://newscenter.lbl.gov/feature-stories/2012/01/05/atom-specific-chemistry/). See also Fig. 3. Another article, "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) appeared in "Science Beat" from the Berkeley Lab and discusses the evolution of the oxygen-evolving complex.

The American Society of Photobiology has posted "Oxygen Evolution" by Charles F. Yocum: http://www.photobiology.info/YocumOxy.html.

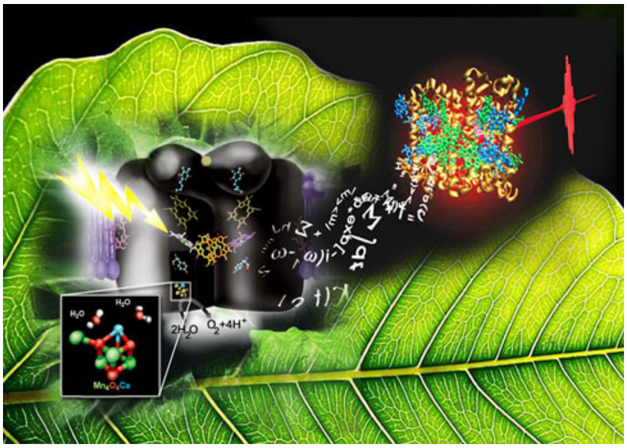

Fig. 3 "An impressionistic look at photosynthesis: at *left*, the oxygen-evolving complex in Photosystem II (Vittal Yachandra/Junko Yano Lab); at *right*, electronic energy transfer in photosystem II's light harvesting complex as simulated by supercomputers at NERSC, the National Energy Research Scientific Computing Center (Graham Fleming group)" (http://newscenter.lbl.gov/feature-stories/2012/01/05/atom-specific-chemistry/)

"The manganese-calcium oxide cluster of Photosystem II and its assimilation by the cyanobacteria" by James D. Johnson covers the evolution of the oxygen evolving complex (http://www.chm.bris.ac.uk/motm/oec/motm.htm). It is a very detailed article with many illustrations.

Wikipedia has a good article on "Oxygen evolution" (http://en.wikipedia.org/wiki/Oxygen_evolution).

The National Renewable Energy Laboratory also has a good site on "Hydrogen & Fuel Cells Research" (http://www.nrel.gov/hydrogen/proj_production_delivery.html) that covers many aspects of water splitting, biological and other.

A 2012 press release (http://www.teknat.umu.se/english/about-the-faculty/news/newsdetailpage/first-snapshots-of-the-electronic-structure-of-a-manganese-complex-related-to-water-splitting-in-photosynthesis.cid202064) from Umeå University describes the use of using an X-ray free-electron laser to study how manganese splits water in photosynthesis.

The light-dependent reactions (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.

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.illinois.edu/govindjee/textzsch.htm. [For the scheme itself, see http://www.life.illinois.edu/govindjee/ZSchemeG.html.]

Wikipedia has a very detailed article covering the "Light-dependent reactions" (http://en.wikipedia.org/wiki/Light-dependent_reactions) with numerous links to related subjects.

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 photophosphorylation (http://faculty.nl.edu/jste/noncyclic_photophosphorylation.htm).

The biology department at Smith University has created a very nice animation that shows four stages of the process (http://www.science.smith.edu/departments/Biology/Bio231/ltrxn.html).

"Cyclic and Noncyclic Photophosphorylation" is a nice animation from McGraw-Hill (http://highered.mcgraw-hill.com/olc/dl/120072/bio12.swf).

The Khan Academy has a couple of useful animated class lectures on the light reactions of use to middle- and high school students. The first is "Photosynthesis: Light Reactions 1" (https://www.khanacademy.org/science/biology/photosynthesis/v/photosynthesis–light-reactions-1). The second is "Photosynthesis: Light Reactions and Photophosphorylation" (https://www.khanacademy.org/science/biology/photosynthesis/v/photosynthesis—light-reactions-and-photophosphorylation). Both are well done in the typical Salman Khan manner.

YouTube video on "Photosynthesis (Light Reactions)" from North Dakota State University is at: http://www.YouTube.com/watch?v=hj_WKgnL6MI (5 min).

A cute YouTube video featuring two well-known babies from television commercials gives an elementary explanation of the "Light and Dark Reactions" (http://www.YouTube.com/watch?v=fVRl4nzMDAU).

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

Although the light-independent carbon cycle is often referred to as the Calvin cycle, it is more accurate to call it the Calvin–Benson cycle to fully acknowledge the contributions of both Melvin Calvin and Andrew Benson to the research that led to its discovery and description.

"The Carbon Cycle" from NASA's Earth Observatory, http://earthobservatory.nasa.gov/Features/CarbonCycle/printall.php, is very detailed and covers a broad area including differences in the carbon cycle on land and in the oceans, the effect of humans on the cycle, and use of satellites to gather data.

Wikipedia has a good article on the Calvin–Benson cycle (http://en.wikipedia.org/wiki/Calvin_cycle) as well as on the "Light-independent reactions" (http://en.wikipedia.org/wiki/Light-independent_reactions).

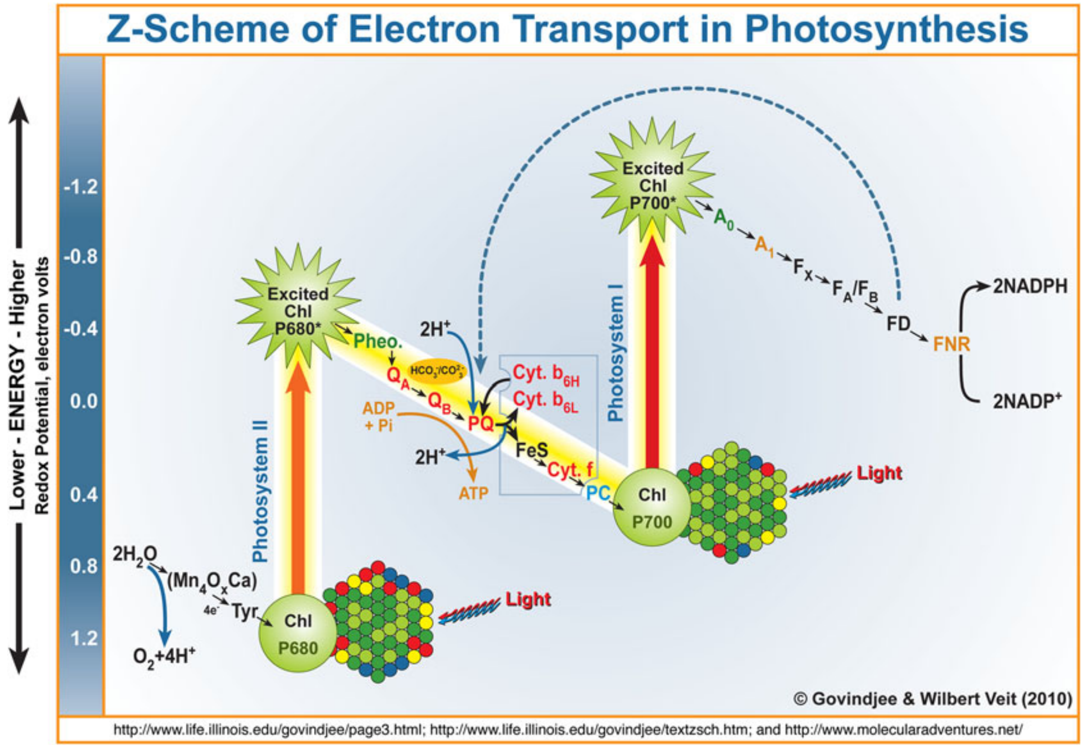

Fig. 4 Z-Scheme of electron transport in photosynthesis by Govindjee and Wilbert Veit, 2010. Full figure legend is available at http://www.life.illinois.edu/govindjee/Z-Scheme.html. [Science teachers in High Schools and Colleges have the possibility of obtaining a copy of this scheme for their classrooms by writing to Govindjee (gov@illinois.edu).]

The Khan Academy video "Photosynthesis: Calvin Cycle" is a good explanation of the Calvin–Benson cycle for advanced middle and high school students (https://www.khanacademy.org/science/biology/photosynthesis/v/photosynthesis-calvin-cycle).

The TED Ed site has a good animated lesson on the carbon cycle by Nathaniel Manning (http://ed.ted.com/lessons/the-carbon-cycle-nathaniel-manning).

From June B. Steinberg of National-Louis University (http://faculty.nl.edu/jste/calvin_cycle.htm), we have a beautifully done site; the steps are clearly shown.

From Smith College, we have interesting animations showing the various steps of the carbon cycle (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.

YouTube video, "Carbon Cycle 2.0" (http://www.YouTube.com/watch?v=k0R43K0pKt0) is a 1 h video, presented by Paul Alivisatos of the Berkeley Lab on the carbon cycle and how human activity is affecting the planet. A related video discusses "Just Say No to Carbon Emissions" (http://www.YouTube.com/watch?v=jAJRWvkx5n8).

The photosynthetic unit/reaction centers

Wikipedia has a good introduction to the "Photosynthetic Reaction Centre" (http://en.wikipedia.org/wiki/Photosynthetic_reaction_centre).

"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).

"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.

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 details of the PSU.

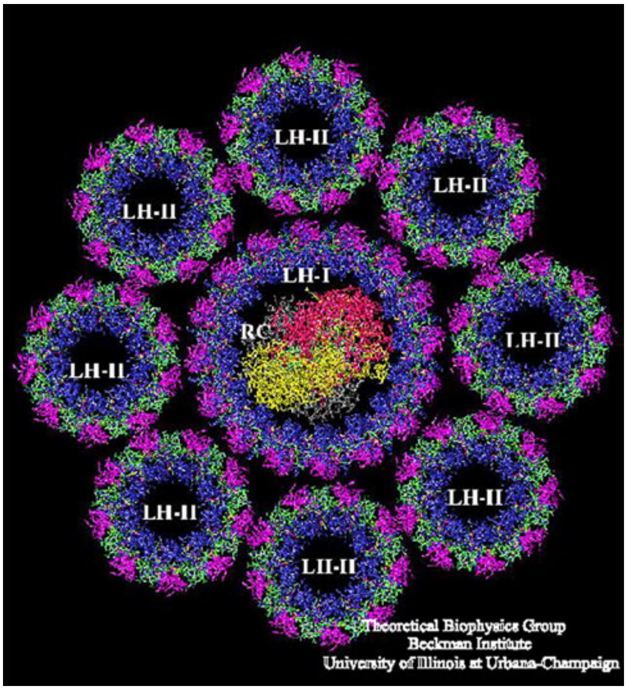

Fig. 5 Structure of the photosynthetic unit from http://www.ks.uiuc.edu/Research/psu/psu.html

The American Society for Photobiology has posted "Photosynthetic Reaction Centers" by Charles Yocum: http://www.photobiology.info/Yocum-PRC.html.

Light-harvesting/antennas

"Photosynthetic Antennas and Reaction Centers: Current Understanding and Prospects for Improvement," by Robert E. Blankenship at Washington University St. Louis (http://bioenergy.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/). See Fig. 6. The group also presents "Inter-Complex Excitation Transfer in photosynthetic bacteria" (http://www.ks.uiuc.edu/Research/psu/psu_inter.html) with 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 (see above) compares light harvesting mechanisms of anoxygenic and oxygenic photosynthetic bacteria.

"Untangling the Quantum Entanglement Behind Photosynthesis" by Graham R. Fleming (http://www.sciencedaily.com/releases/2010/05/100510151356.htm) discusses quantum entanglement in light harvesting complexes.

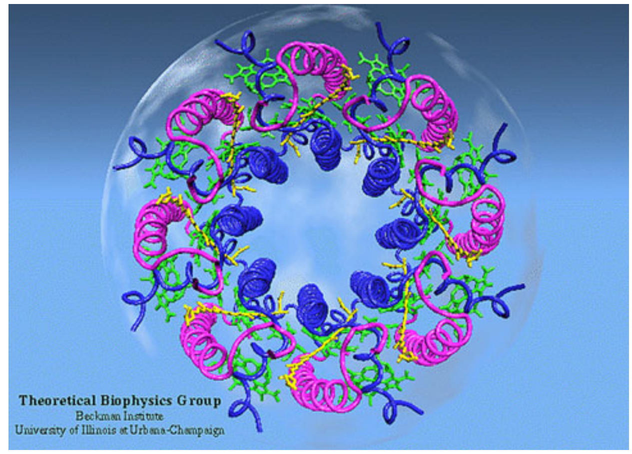

Fig. 6 Light-harvesting complex from the Theoretical Biophysics Group, UIUC (http://www.ks.uiuc.edu/Research/bio_ener/LH_2/lh2-big.gif)

The Wikipedia article on the "Light Harvesting Complex" (http://en.wikipedia.org/wiki/Light_harvesting_complex) is a good introduction to the complex. A second Wikipedia article covers "Light-harvesting complexes of green plants" (http://en.wikipedia.org/wiki/Light-harvesting_complexes_of_green_plants).

Electron transfer

Electron transfer is described at the following site: http://www.rpi.edu/dept/bcbp/molbiochem/MBWeb/mb1/part2/redox.htm.

The Marcus equation for electron transfer is given at http://goldbook.iupac.org/M03702.html. The interactive link maps on this site link to many very important equations.

"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.illinois.edu/govindjee/textzsch.htm. [For the scheme itself, see http://www.life.illinois.edu/govindjee/ZSchemeG.html.] However for a 2010 scheme, see Fig. 4, shown above.

Wikipedia has a lengthy article on the "Electron transport chain" (http://en.wikipedia.org/wiki/Electron_transport_chain) that covers several aspects of the subject.

YouTube includes a brief video on the "Electron-Transport Chain" from *Essential Cell Biology*, 3rd edition (http://www.YouTube.com/watch?v=KXsxJNXaT7w&feature=related) (2:16 min).

Bacterial photosystem/Photosystems I and II

The Protein Data Bank has excellent information on both Photosystem I (http://www.rcsb.org/pdb/101/motm.do?momID=22) and Photosystem II (http://www.rcsb.org/pdb/101/motm.do?momID=59).

John Golbeck has posted an excellent PDF, "Photosynthetic Reaction Centers: So little time, so much to do", a discussion of PS I that can be found at: http://www.biophysics.org/Portals/1/PDFs/Education/golbeck.pdf.

Carl Bauer's lab at Indiana University (http://sites.bio.indiana.edu/~bauerlab/): The site contains nice descriptions and figures for several research projects, e.g., photosystem gene regulation by oxygen and light. It also has information on the origin and evolution of bacterial photosynthesis. You can click on an individual topic.

"Shedding New Light on the Earth's Powerstation" from The US National Aeronautics and Space Administration (NASA) describes the crystallizing of Photosystem I (PSI) on the space shuttle (http://science.nasa.gov/science-news/science-at-nasa/1998/msad27jul98_1/) 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).

The Virtual Cell Animation Collection at North Dakota State University has a good article and flash animations on "Photosystem II: First Look" (http://vcell.ndsu.nodak.edu/animations/photosystemII/first.htm).

"Photosystem II" (http://www.life.illinois.edu/crofts/ahab/psiiwork.html) is a good sites to learn about Photosystem II.

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

Wikipedia has good articles on both Photosystem I (http://en.wikipedia.org/wiki/Photosystem_I) and Photosystem II (http://en.wikipedia.org/wiki/Photosystem_II).

The Theoretical and Computational Biophysics Group at the University of Illinois covers "The Tale of Two Photosystems" (http://www.ks.uiuc.edu/Research/psres/plantps1.html) in a discussion of the differences of the types of Photosystem I found in cyanobacteria and plants.

"Catching some rays: Harnessing the power of photosynthesis" (http://researchmatters.asu.edu/stories/catching-some-rays-harnessing-power-photosynthesis-945) discusses the evolution of Photosystems I and II. X-ray crystallography is used by Petra Fromme to determine the structure of PS I (Fig. 7).

YouTube video: "Light capture by Photosystem I" (http://www.YouTube.com/watch?v=UsV-PL3dJA0). YouTube has a good brief animated video on "Photosystem II" (http://www.YouTube.com/watch?v=3UfV060N27g) showing the electron transfer process. The video is provided by the Virtual Cell Animation Collection, from North Dakota State University.

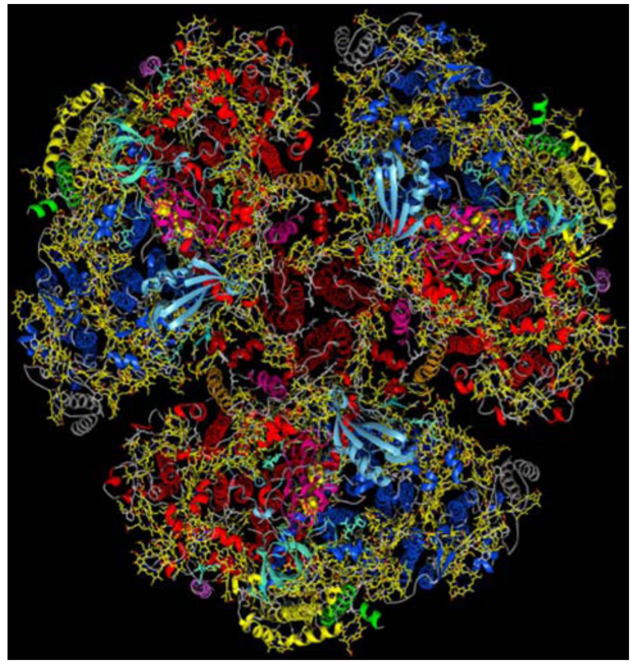

Fig. 7 Structure of Photosystem I determined using X-ray crystallography in Petra Fromme's lab at Arizona State University

Cytochromes and cytochrome oxidase

"Models for Cytochrome *c* Biogenesis" from Robert Kranz at the University of Hamburg (http://www.biologie.uni-hamburg.de/b-online/ibc99/wustl/faculty/kranz/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.

"The bc1-Complex Site" from Antony Crofts at the University of Illinois at Urbana (http://www.life.illinois.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 *b6f* Complex" on William Cramer's Web page at Purdue University (http://www.bio.purdue.edu/lab/cramer/cytbf.html): Here, you will find an excellent description of this complex.

The University of Arizona has created a very nice interactive site "Cytochrome *c* and Cytochrome *c* Oxidase" with animations and structures that can be accessed from the panel on the right. The structures then appear in the main window and can be manipulated by the user. Very nicely done (http://www.biochem.arizona.edu/classes/bioc463a/molecular_graphics_gallery/jmol/cytc_music_m/cytc.html).

Wikipedia has brief articles on "Cytochrome" (http://en.wikipedia.org/wiki/Cytochrome) and "Cytochrome c oxidase" (http://en.wikipedia.org/wiki/Cytochrome_c_oxidase).

ATP synthase

"ATP Synthase" by John Walker, the work that won him the Nobel Prize (http://www.mrc-mbu.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-mbu.cam.ac.uk/research/atp-synthase/molecular-animations-atp-synthase) and breakdown of the subunits (http://www.mrc-mbu.cam.ac.uk/research/atp-synthase/structures-domains-atp-synthase) (Fig. 8). The rotary mechanism video is also available on YouTube (http://www.YouTube.com/watch?v=J8lhPt6V-yM&feature=related).

"Animation Movies of ATP Synthase" by Hongyun Wang and George Oster of University of California, Santa Cruz and Berkeley (http://users.soe.ucsc.edu/~hongwang/Project/ATP_synthase/) are great fun. Enjoy the site and learn from it.

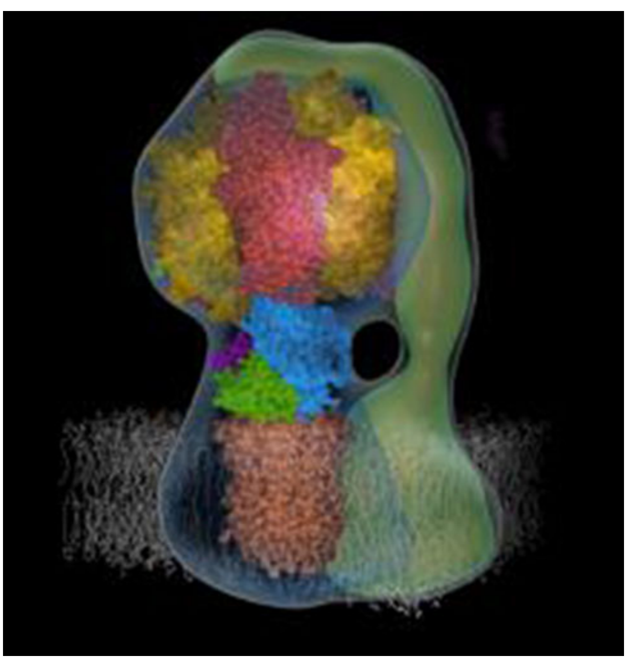

Fig. 8 Rotary mechanism of ATP synthase from John Walker's Web site: http://www.mrc-mbu.cam.ac.uk/research/atp-synthase/molecular-animations-atp-synthase

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

"The Photosynthetic ATP Synthase: Assembly of Hybrid Complexes from Bacterial and Plant Subunits Defines Their Roles in Catalysis" by the late 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. (Her obituary appears in Photosynthesis Research, volume 96: 117–119.)

Wikipedia has a good article on "ATP synthase" (http://en.wikipedia.org/wiki/ATP_synthase).

Video from Dnatube "ATP Synthase Structure and Mechanism" is a good computer animation and explanation of the activity of ATP synthase (http://www.dnatube.com/video/104/ATP-synthase-structure-and-mechanism) (3:19 min).

Boris A. Feniouk maintains the "ATP Synthase Web Page" (http://www.atpsynthase.info/) with many links to information, papers, images, and more.

YouTube video "Gradients (ATP Synthases)" from North Dakota State University (http://www.YouTube.com/watch?v=3y1dO4nNaKY) (3:46 min).

C3, C4 and CAM (Crassulacean 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.

Brad Fiero of Pima Community College presents a brief, easily understood definitions of C3, C4 and CAM photosynthesis (http://wc.pima.edu/~bfiero/tucsonecology/plants/plants_photosynthesis.htm), highly recommended for students.

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/.

For fun, a low-budget YouTube video featuring sock puppets doing the "C4 Photosynthesis Rap" (http://www.YouTube.com/watch?v=Ux1eted7nGE). LOL!

Wikipedia has brief articles on "C3 carbon fixation" (http://en.wikipedia.org/wiki/C3_carbon_fixation), "C4 carbon fixation" (http://en.wikipedia.org/wiki/C4_carbon_fixation), and "CAM photosynthesis" (http://en.wikipedia.org/wiki/Crassulacean_acid_metabolism).

The Kahn Academy also has video lessons on "C-4 Photosynthesis" (https://www.khanacademy.org/science/biology/photosynthesis/v/c-4-photosynthesis) and "CAM Plants" (https://www.khanacademy.org/science/biology/photosynthesis/v/cam-plants?playlist=Biology).

Chlorophyll fluorescence

"Chlorophyll Fluorescence and Definitions" 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) (http://jaguar.fcav.unesp.br/download/deptos/biologia/durvalina/TEXTO-71.pdf): It is a reference paper (PDF) with many figures and references for students.

Govindjee has also set up a page for the Kautsky Effect with a QuickTime movie showing the effect (http://www.life.illinois.edu/govindjee/movkautsky.html). A QuickTime plug-in is required.

"Chlorophyll fluorescence—a practical guide" (http://jxb.oxfordjournals.org/cgi/content/full/51/345/659) is a well-written review article provided as a service to schools by 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).

Chlorophyll a Fluorescence: A Signature of Photosynthesis, edited by G. C. Papageorgiou and Govindjee, is now available in softcover as well as an e-book at libraries that subscribe to it. Readers can download free Front Matter of the book, which includes all the colored plates (http://www.springerlink.com/content/978-1-4020-3217-2).

Wikipedia has an article on "Chlorophyll fluorescence" (http://en.wikipedia.org/wiki/Chlorophyll_fluorescence).

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 and a link to a Spanish version.

"Photosynthesis Inhibitors" (http://www.btny.purdue.edu/weedscience/MOA/Photosynthetic_Inhibitors/text.html) from the Department of Botany at Purdue includes brief descriptions and also time-lapse videos.

"How Herbicides Work" (http://www.uri.edu/ce/factsheets/sheets/herbicides.html) from the University of Rhode Island Landscape Horticulture Program.

"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.illinois.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 "innards" of the chloroplast.

The American Society for Photobiology has posted "Light and Chloroplast Enzyme Activity" by Peter Schürmann: http://www.photobiology.info/Schurmann.html.

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

"Biological antennae also need to be tuned…" (http://personal.rhul.ac.uk/uhba/047/index.htm) 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.

"The Chloroplast Genome and Chloroplast Gene Expression" (http://hstalks.com/main/view_talk.php?t=522&r=14&j=755&c=252) is a video talk by Christopher Howe discussing the chloroplast genome.

Wikipedia has a good article with numerous figures on "Chloroplast" (http://en.wikipedia.org/wiki/Chloroplast).

YouTube video: "Bill Nye The Science Guy—Chloroplasts" is not really by Bill Nye, but a fun student bio project featuring cardboard cutouts explaining the structure of chloroplasts (http://www.YouTube.com/watch?v=dax7v711qg0&feature=related). Wacky fun and sometimes out-of-control.

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.

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 (International Union of Pure and Applied Chemistry) 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.

For a 1998 article on a historical perspective on carotenoids in photosynthesis, "Carotenoids in Photosynthesis: An Historical Perspective," go to: http://www.life.illinois.edu/govindjee/papers/CarFin1.html.

The Linus Pauling Institute at Oregon State University presents "Carotenoids" (http://lpi.oregonstate.edu/infocenter/phytochemicals/carotenoids/) devoted to the uses of carotenoids in nutrition.

Wikipedia article on "Carotenoid" (http://en.wikipedia.org/wiki/Carotenoid).

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/RubJmol/Rubisco%20proj/Title_Page.html): A bit out of date, but is still a very good site that tells you what Rubisco is, its mechanism of action and provides many useful references. (Note: use the Jmol version as this plug-in is included in Java aware browsers. The Chime versions are no longer working.)

The Protein Data Bank covers "Rubisco" (http://www.rcsb.org/pdb/101/motm.do?momID=11) in detail. See Fig. 9.

Wikipedia has a very good article on Rubisco (http://en.wikipedia.org/wiki/RuBisCO). As usual, we would like the readers to read "Calvin cycle" as "Calvin–Benson" cycle.

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).

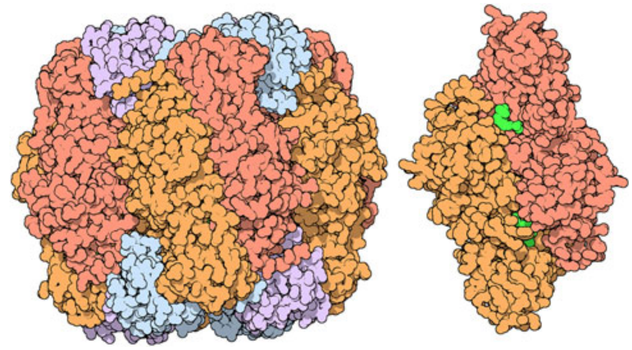

Fig. 9 Rubisco from the Protein Data Bank (http://www.rcsb.org/pdb/101/motm.do?momID=11)

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); USDA-ARS sites in Arizona studying effects on cotton and wheat (http://www.ars.usda.gov/research/projects/projects.htm?accn_no=409185); 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://public.ornl.gov/face/global_face.shtml. 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://soyface.illinois.edu/index.htm. Some of the photos in the middle of the top banner are those of two of the leaders there: Steven Long (http://www.life.illinois.edu/long/) and Donald R. Ort (http://www.life.illinois.edu/ort/).

"Field Photosynthesis Measurement Systems" from New Mexico State University (http://hydrology1.nmsu.edu/Teaching_Material/soil698/Student_Material/Photosynthesis/): This site describes LICOR Gas exchange systems and their use for measuring whole plant photosynthesis.

Wikipedia does a good job covering "Plant stress measurement" (http://en.wikipedia.org/wiki/Plant_stress_measurement).

The "Plant Stress Genomics Research Center (PSGR)" (http://www.kaust.edu.sa/research/centers/plant.html) at King

Abdullah University of Science and Technology studies how plants tolerate salt and drought conditions.

NASA's "Plant Stress Paints Early Picture of Drought" (http://www.nasa.gov/topics/earth/features/plant-stress.html) covers the multi-year drought in the US, including a video showing drought trends.

"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 and revised in 2010.

The Fleming group at the Berkeley lab discusses "How are photosynthetic organisms able to protect themselves from energy-related damage?" (http://www.cchem.berkeley.edu/grfgrp/pages/Question_Pages/NPQ.html) The article discusses dissipation of excess excitation energy and non-photochemical quenching.

YouTube video "the Plant That Doesn't Feel the Cold" from the John Innes centre in Norwich, UK, discusses modifying plants to better deal with temperature stress and climate change (http://www.YouTube.com/watch?v=3KmT5xlCaC4&feature=player_embedded).

Bacterial photosynthesis

Mike Jones from the University of Bristol provides "Bacterial Photosynthesis" (http://www.photobiology.info/Jones.html); it is a good introduction to the subject.

"Introduction to the Cyanobacteria" [cyanobacteria are oxygenic photosynthesizers] 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 these cyanobacteria changed the very atmosphere we breathe, and led to the existence of plants.

"Purple Non-Sulfur Photosynthetic Bacteria" [these bacteria are anoxygenic photosynthesizers] 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.

The American Society of Photobiology has posted "Bacterial Photosynthesis" by Mike Jones: http://www.photobiology.info/Jones.html.

"Chlorobi: Green Sulfur Bacteria" (http://bmb-it-services.bmb.psu.edu/bryant/lab/Project/GSB/index.html) by Don Bryant at Penn State University contains introductory information on the green sulfur bacteria and links to genomic information.

Niels-Ulrik Frigaard at the University of Copenhagen discusses "Molecular Microbial Physiology" (http://www.bio.ku.dk/nuf/) with emphasis on the phototrophic sulfur bacteria, cyanobacteria, marine bacteria and much more.

YouTube video: "Photosynthesis in Bacteria (Rhodopseudomonas Viridis)" (http://www.YouTube.com/watch?v=J5Nz4cQJ2u8) gives a simple animated introduction to bacterial photosynthesis.

Evolution of photosynthesis

"Early Evolution of Photosynthesis" by Robert E. Blankenship (http://www.plantphysiol.org/content/154/2/434.full) was first published in Plant Physiology in 2010. It is now available to the general public and is a very good introduction to the subject. PDF versions and even PowerPoint files are included.

"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.

"When did oxygenic photosynthesis evolve?" by Roger Buick (http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2606769/) discusses the "Great Oxidation Event" and its relationship to biological oxygen production.

"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 bacteria. It is very complete and contains many good illustrations and chemical structures.

"Geobiologists Solve 'Catch-22 Problem' Concerning the Rise of Atmospheric Oxygen" (http://www.caltech.edu/content/geobiologists-solve-catch-22-problem-concerning-rise-atmospheric-oxygen) 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.

"Using the present to inform the past: interpreting potential biomarkers of (an)oxygenic photosynthesis" (http://www.dknlab.caltech.edu/Metabolism.html) is a discussion of the evolution of photosynthesis from Dianne K. Newman's lab at MIT. She also has a video on "From Rocks to Genes and Back: Stories About the Evolution of Photosynthesis"; it is a lecture given at an MIT seminar (http://video.mit.edu/watch/from-rocks-to-genes-and-back-stories-about-the-evolution-of-photosynthesis-9299/) (43 min).

Paul Falkowski discusses "Electrons, Life and the Evolution of the Oxygen Cycle on Earth" another video lecture in the MIT series (http://video.mit.edu/watch/electrons-life-and-the-evolution-of-the-oxygen-cycle-on-earth-9298/) (53:35 min). Falkowski's talk begins at about the 5 min mark.

Photosynthesis and the environment/global climate change

"The Climate Desk" (http://theclimatedesk.org/) is a collaboration of writers from the *Atlantic*, *Grist*, *Mother Jones*, *Wired*, *Slate*, and others. It features reprint articles about the impact of global climate change on humans, the environment, economies, and politics. It also has a Facebook site: http://www.facebook.com/theclimatedesk.

The National Climatic Data Center (NCDC) and National Oceanic and Atmospheric Administration (NOAA) have set up a very good FAQ site for "Global Warming" (http://www.ncdc.noaa.gov/oa/climate/globalwarming.html).

NASA presents "Global Climate Change: Vital Signs of the Planet" (http://climate.nasa.gov/) with much good information and good links. A special section is devoted to "Climate Kids" (http://climatekids.nasa.gov/) with information for younger students.

The Intergovernmental Panel on Climate Change (IPCC) has set up a site with a great deal of information (http://www.ipcc.ch/). There are links to their reports, meetings, figures and much more, including links to the controversies regarding possible errors in the research.

350.org (http://350.org) is a major blog discussing climate change and a grass roots organization dedicated to reducing the amount of CO_2 from its current level of 392 parts per million to below 350 ppm.

The Center for Climate and Energy Solutions (C2ES) (http://www.c2es.org/) covers governmental policies at the local, national and international levels as well as covering environmental aspects of technology, science and business.

A Wikipedia presentation on "Climate change denial" that is used to describe attempts to downplay the extent of global warming and its impact: http://en.wikipedia.org/wiki/Climate_change_denial.

The iTunes Open University site has set up a section on "Environment, Development and International Studies" which have good sections on "Environmental ethics," "Energy policy and climate change" and more. Access to the sites is through the iTunes store via the Internet.

"Greenhouse Gases and Society" by Nick Hopwood and Jordan Cohen from the University of Michigan (http://pratclif.com/climatechange/Greenhouse%20Gases.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/issue7/greenhouse.pdf) by Kristen DeAnglis discusses work being done at UC-Berkeley. It is a good general article in PDF format that discusses the problem and its complexities.

The U.S. Environmental Protection Agency (EPA) has a substantial Web site 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/). The EPA site also has a student's guide to "Global Climate Change" (http://www.epa.gov/climatechange/students/index.html) with simple explanations and links.

"RealClimate" (http://www.realclimate.org/) is an important site for information on climate change information written by working climate scientists. It has sections for beginners and those with more knowledge about climate change issues.

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

"Photoinhibition in Antarctic Phytoplankton by Ultraviolet-B Radiation in Relation to Column Ozone Values" from US National Science Foundation's (NSF's) Office of Polar Programs (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.

William Calvin, from the University of Washington, presents information about climate change, including his famous lectures, at http://www.williamcalvin.com/index.html.

"Teaching Climate Change: Lessons for the Past" from Carleton University (http://serc.carleton.edu/NAGTWorkshops/climatechange/index.html) presents a comprehensive list of resources to help understand and teach about climate change at many levels. Highly recommended. They also have a second site "Teaching About Energy in Geoscience Courses" (http://serc.carleton.edu/NAGTWorkshops/energy/index.html) that also contains useful links.

YouTube video: "Singing Minstrels—Teaching Kids about Climate Change" (http://www.YouTube.com/watch?v=DguUQamkH0A) (28 min). Environmental educators use music to teach children about climate change.

History of photosynthesis/biographies/nobel prizes

The American Society of Photobiology has posted "Photosynthesis Timelines" by Thomas Brennan: http://www.photobiology.info/History_Timelines/Hist-Photosyn.html.

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

James Fulton from Suffolk County Community College has written a long informative outline of "The History of Photosynthesis" covering many historical events to 1988 that is available as a Word document (http://www2.suny suffolk.edu/fultonj/SUNY_Suffolk_Resources/Math_Laboratories/Lab_3/hist.doc).

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.illinois.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, is available at: http://www.life.illinois.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.

Jane Hill has recently published "Chemical Research on Plant Growth: A translation of Théodore de Saussure's Recherches chimiques sur la Végétation (2013)". See http://www.amazon.com/Chemical-Research-Plant-Growth-translation/dp/1461441358. It is a wonderful translation and explanation of de Saussure's groundbreaking work on photosynthesis.

Other important historical documents are:

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

A large number of Personal Perspectives, autobiographical retrospectives, edited by Govindjee et al., and published in the international journal *Photosynthesis Research* are found at: http://www.life.illinois.edu/govindjee/g/PhotoEdHistory.html. Although these perspectives usually may not contain large amounts of science, they do discuss the major discoveries by 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." Over 100 of these perspectives by 132 authors in 19 countries have been collected in *Discoveries in Photosynthesis*, edited by Govindjee, J. Thomas Beatty, Howard Gest and John F. Allen (http://www.life.illinois.edu/govindjee/newbook/Vol%2020.html). The table of content of this book is available at http://www.springerlink.com/content/978-1-4020-3323-0; also, you can download the Front Matter and the Back Matter. A few of the earlier perspectives are available as PDF files.

David Krogmann (http://www.life.illinois.edu/govindjee/history/KrogmannDavidPP.pdf), R. Clint Fuller (http://www.life.illinois.edu/govindjee/history/FullerClintPP.pdf), Giorgio Forti (http://www.life.illinois.edu/govindjee/history/FortiGeorgioPP.pdf), André Jagendorf (http://www.life.illinois.edu/govindjee/history/JagendorfAndrePP.pdf), George Feher (http://www.life.illinois.edu/govindjee/history/FeherGeorgePP.pdf), David Walker (http://www.life.illinois.edu/govindjee/history/WalkerPP.pdf).

Govindjee has also edited several obituaries that have been published (http://www.life.illinois.edu/govindjee/history/obituaries.htm), with some of them available online as PDF files. Others are available at the Web site of *Photosynthesis Research* (http://www.springerlink.com/content/100325/), available free to members of the International Society of Photosynthesis Research (ISPR), or at your local library if they subscribe to the journal.

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), Joseph Priestley (http://webserver.lemoyne.edu/faculty/giunta/phlogiston.html). Another paper of interest includes early work on the greenhouse effect by Svante Arrhenius (http://web.lemoyne.edu/~giunta/Arrhenius.html). Besides these, there are many other selected classic papers from the history of chemistry (http://web.lemoyne.edu/~giunta/paperabc.html).

Today in Science History has a listing of brief, but important, quotations from historical figures such as van Helmont, Ingenhousz, etc. (http://www.todayinsci.com/QuotationsCategories/P_Cat/Photosynthesis-Quotations.htm). The site also has an interesting story about "The Sun as a Chemist" (http://www.todayinsci.com/stories/story054.htm). A sample: "Indeed, instead of building factories, furnishing them with unique equipment and working out complex synthesis technologies, it will only be necessary to build hothouses and to regulate the intensity and spectral composition of the light rays used. Then the plants themselves will make everything required: from the simplest carbohydrates to the most complex proteins."

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

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. His work is discussed at: http://nobelprize.org/nobel_prizes/chemistry/laureates/1915/present.html and his biography is at: http://nobelprize.org/nobel_prizes/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://nobelprize.org/nobel_prizes/physics/laureates/1925/press.html) and his biography (http://nobelprize.org/nobel_prizes/physics/laureates/1925/franck-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://nobelprize.org/nobel_prizes/physics/laureates/1930/press.html. His biography is at http://nobelprize.org/nobel_prizes/physics/laureates/1930/raman-bio.html.

Hans Fischer, Chemistry, 1930, won for his work on porphyrins and blood and leaf pigments, particularly chlorophyll: http://nobelprize.org/nobel_prizes/chemistry/laureates/1930/press.html. His biography is at http://nobelprize.org/nobel_prizes/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://nobelprize.org/nobel_prizes/medicine/laureates/1931/press.html. His biography is at http://nobelprize.org/nobel_prizes/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). [This is discussed by Govindjee (1999) in Photosynthesis Research 59, 249–254; and in details by K. Nickelsen and Govindjee (2011) The Maximum Quantum Yield Controversy: Otto Warburg and the ≪Midwest-Gang≫, Bern Studies in the History and Philosophy of Science.]

Paul Karrer, Chemistry, 1937, won for his work on carotenoids, flavins and vitamins: http://nobelprize.org/nobel_prizes/chemistry/laureates/1937/press.html. His biography is at http://nobelprize.org/nobel_prizes/chemistry/laureates/1937/karrer-bio.html.

Richard Kuhn, Chemistry, 1938, won for additional work on carotenoids and vitamins: http://nobelprize.org/nobel_prizes/chemistry/laureates/1938/press.html. His biography is at http://nobelprize.org/nobel_prizes/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://nobelprize.org/nobel_prizes/medicine/laureates/1959/ochoa-bio.html.

Melvin Calvin, Chemistry (Fig. 10), 1961, won for his work on carbon dioxide assimilation in photosynthesis, the carbon cycle, also named "The Calvin cycle" after him: http://nobelprize.org/nobel_prizes/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 A. A. Benson (2005) in *Discoveries in Photosynthesis*, pp. 793–813, Springer, for his contributions.). Calvin's biography is at http://nobelprize.org/nobel_prizes/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: http://www.life.illinois.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://nobelprize.org/nobel_prizes/chemistry/laureates/1965/press.html. His biography is at http://nobelprize.org/nobel_prizes/chemistry/laureates/1965/woodward-bio.html.

George Porter, Chemistry, 1967, won for his development of flash photolysis (along with Ronald Norrish). Lord

Fig. 10 Andrew Benson (*right*) with Melvin Calvin (*left*) outside of the Old Radiation Laboratory (ORL); here Benson is showing Calvin his new Exakta camera that he had bought in Köln, Germany. Photo, 1950s

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://nobelprize.org/nobel_prizes/chemistry/laureates/1967/press.html. His biography is at http://nobelprize.org/nobel_prizes/chemistry/laureates/1967/porter-bio.html. His obituary (for subscribers) in *Nature* is available at http://www.nature.com/nature/journal/v419/n6907/full/419578a.html.

Peter D. Mitchell, Chemistry, 1978, won for his work on biological energy transfer through the formulation of the chemiosmotic theory: http://nobelprize.org/nobel_prizes/chemistry/laureates/1978/press.html. His biography is at http://nobelprize.org/nobel_prizes/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://nobelprize.org/nobel_prizes/chemistry/laureates/1982/press.html. His autobiography is at http://nobelprize.org/nobel_prizes/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://nobelprize.org/nobel_prizes/chemistry/laureates/1987/press.html. His autobiography is at http://nobelprize.org/nobel_prizes/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://nobelprize.org/nobel_prizes/chemistry/laureates/1988/press.html. Deisenhofer's autobiography is at http://nobelprize.org/nobel_prizes/chemistry/laureates/1988/deisenhofer-autobio.html. Huber's is at http://nobelprize.org/nobel_prizes/chemistry/laureates/1988/huber-autobio.html. And Michel's is at http://nobelprize.org/nobel_prizes/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://nobelprize.org/nobel_prizes/chemistry/laureates/1992/press.html. His autobiography is at http://nobelprize.org/nobel_prizes/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://nobelprize.org/nobel_prizes/chemistry/laureates/1993/press.html. His autobiography may be found at: http://nobelprize.org/nobel_prizes/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://nobelprize.org/nobel_prizes/chemistry/laureates/1997/press.html. Boyer's autobiography is at http://nobelprize.org/nobel_prizes/chemistry/laureates/1997/boyer-autobio.html, and Walker's is at http://nobelprize.org/nobel_prizes/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://nobelprize.org/nobel_prizes/chemistry/laureates/1999/press.html. His autobiography may be found at: http://nobelprize.org/nobel_prizes/chemistry/laureates/1999/zewail-autobio.html.

Individual researcher's sites

In this section we list a number of individual sites that we feel are well done. Most scientists have sites set up by their academic department but those often contain little more than contact information, very brief politically correct information on research and perhaps a curriculum vitae (CV) and a list of publications. 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. It is our opinion that a multi-layered site reveals the richness of the researcher's personality and lab group. We feel that potential students might be attracted to those that take the time to set up a rich site over simple cookie-cutter sites. 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://bioenergy.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://queenmaryphotosynthesis.org/~john/index.html) contains much useful information. Also see his older site (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 Web site.

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

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://pages.wustl.edu/blankenshiplab/photo-gallery/alvin-trip) 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.illinois.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.illinois.edu/cheeseman/photosynthesis/main.html. And don’t forget to check out the links to the “Erratic Crab” where you will learn things like “How much data would a data manager manage if a data manager could get your data?” (http://www.life.illinois.edu/cheeseman/ecrab/ECv1n2/).

Richard J. Cogdell (http://www.gla.ac.uk/researchinstitutes/biology/staff/richardcogdell/) Follow the links to a very rich Web site with incredible images of light-harvesting complex II and the reaction centers (Fig. 11).

William Cramer (http://www.bio.purdue.edu/lab/cramer/). Contains good descriptions and figures of work with the structure of cytochrome *b*6*f* complex, cytochrome *f* and the Rieske iron–sulfur protein.

Antony Crofts (http://www.life.illinois.edu/crofts/). This site is a virtual goldmine of information. There is much here on the cytochrome *bc*1 complex and many other subjects, including many helpful links. It contains a good cartoon animation of the Rieske Iron sulfur protein.

Charles Dismukes (http://dismukeslab.99k.org/). 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 and photos of past and present lab members are always intriguing. Also check out his lab’s work on quantum mechanical effects in photosynthesis (http://www.lbl.gov/Science-Articles/Archive/PBD-quantum-secrets.html) that adds new ideas and concepts of coherence to the existing energy transfer models.

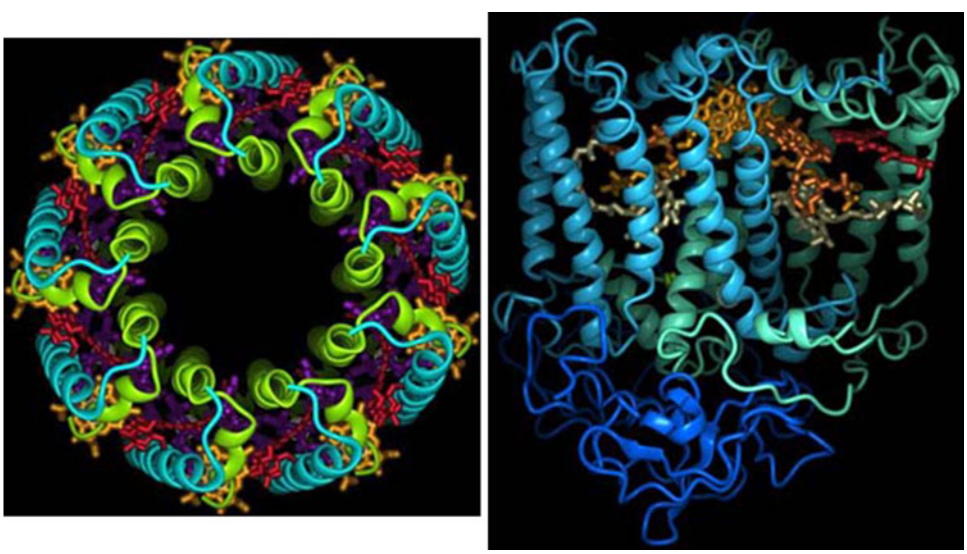

Fig. 11 Structure of light harvesting complex 2, LH2 (*left*) from *Rps. acidophila* strain 10050 and the reaction center (*right*) from *Rhodobacter sphaeroides* from Richard Cogdell’s Web site (http://www.gla.ac.uk/researchinstitutes/biology/staff/richardcogdell/)

Harry Frank (http://frankgroup.uconn.edu/). 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 (Fig. 12!) playing his song "melted carrot" as well as great discussion of carotenoids (http://frankgroup.uconn.edu/frank_podcast.html), and lots more. This is one of our favorite sites for its scientific as well as personal presentations. You can also check out his Facebook page at http://www.facebook.com/profile.php?id=1132602120&v=info&ref=name.

Petra Fromme (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.

Govindjee (http://www.life.illinois.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.illinois.edu/govindjee/PSed_index.htm. Research publications in the areas of primary photochemistry; role of bicarbonate in Photosystem II; chlorophyll *a* fluorescence, among other topics can be found arranged chronologically, as well as according to journals and to topics. A fun place is where photos of

Fig. 12 Harry Frank: photosynthetic musician, author of "melted carrot," http://frankgroup.uconn.edu/frank_podcast.html

students receiving awards are shown. See, e.g., http://www.life.illinois.edu/govindjee/photooftheyear2012.html.

A useful basic educational material is his 1969 book on Photosynthesis, with E. Rabinowitch (http://www.life.illinois.edu/govindjee/photosynBook.html). [Also see http://www.life.illinois.edu/govindjee/g/Books.html for other books.] In August, 2007, he was presented 2nd International Society of Photosynthesis Research's Communication Award for his outstanding efforts in communicating basic and advanced information on all aspects of photosynthesis, including history of photosynthesis research, through his lectures, reviews, many edited volumes and his series (*Advances in Photosynthesis and Research*). There are photographs of scientists and complete information on several volumes of the *Advances in Photosynthesis and Respiration*. A 34 min interview of Govindjee for the Annual Reviews Inc. can be found at http://www.YouTube.com/watch?v=cOzuL0vxEi0.

Harry B. Gray is a chemist at Caltech studying how we can use solar energy to power our world. "Harry Gray: Powering the Planet with Solar Fuel" (http://www.YouTube.com/watch?v=fwqVsRLHq24) is a YouTube video of Harry B. Grays's hour-long presentation on solar fuel. We are pleased that Northwestern University preserved this interesting lecture. Another YouTube video featuring Harry Gray, "Passion for Science" (http://www.YouTube.com/watch?v=rpJPLptlGVU) discusses how his interest in pigments led to his solar energy studies. EarthSky's site (http://earthsky.org/energy/harry-grays-solar-fuel-cells-will-create-fuel-from-sunlight) features a link to an 8-min interview that discusses solar energy and artificial photosynthesis.

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).]

Kazuhito Hashimoto (http://www.light.t.u-tokyo.ac.jp/english/index.htm) contains information on artificial photosynthesis, photocatalysis and environmental issues featuring solar technologies.

Alfred R. Holzwarth (http://www.mpibac.mpg.de/bac/mitarbeiter/holzwarth/holzwarth_en.php) Contains information on artificial photosynthesis, Photosystems I & II, antenna systems and more.

Anne Jones (http://bioenergy.asu.edu/faculty/jones/research.html) studies redox enzymes and how these catalysts work, offering exciting possibilities in such diverse fields as renewable energy generation, biological synthesis, and homogeneous catalysis. Her work on artificial hydrogenases is key to developing some artificial photosynthesis systems.

Stephen Long (http://www.life.illinois.edu/long/index.html). This site contains much information on alternative fuels and crops (http://www.life.illinois.edu/long/Media.html) and links to other projects such as SoyFACE (http://soyface.illinois.edu/index.htm) and WIMOVAC (http://www.life.illinois.edu/plantbio/wimovac/), projects studying environmental factors that might influence climate change.

Jörg Matysik (http://www.cidnp.net) studies the nuclear polarization occurring during the photosynthetic primary reaction with optical NMR methods. Photo-CIDNP MAS NMR is used to map electronic structures of donors at atomic resolution.

Anastasio Melis (http://pmb.berkeley.edu/profile/amelis) 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 (with links to the famous "The Elements of Style" by William Strunk on line, loved by us); dictionaries; on-line journals; and genome databases. 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://discovermagazine.com/1995/feb/whitherthey470) that both of the editors needed to read! 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.colbertnation.com/the-colbert-report-videos/173859/june-16-2008/kenneth-miller). "The collapse of intelligent design, will the next monkey trial be in Ohio?" is Miller's 2-h lecture (that begins, interestingly, with a prayer) in which he rips apart Intelligent Design (http://www.YouTube.com/watch?v=JVRsWAjvQSg&feature=related).

Thomas A. Moore (http://bioenergy.asu.edu/faculty/tmoore/) is the director of the Arizona State University Center for Bioenergy & Photosynthesis. Besides the usual description of his research interests, it includes information about climate change and essays about the importance of taking immediate action. There are also side trips to more personal areas such as Jazz and Blues music, especially Texas Blues.

Jon Nield at Queen Mary, University of London (http://www.queenmaryphotosynthesis.org/nield/) has an incredibly rich site that covers the major protein complexes involved in photosynthesis. There are numerous discussions and incredible figures available for download from the gallery. Even more downloads and information is available at http://www.queenmaryphotosynthesis.org/nield/downloads.html. See Fig. 13.

Daniel Nocera at MIT (http://web.mit.edu/chemistry/dgn/www/) is involved with a number of research projects including "Solar Energy Conversion" (http://web.mit.edu/chemistry/dgn/www/research/solar.shtml) and "Proton-Coupled Electron Transfer" (http://web.mit.edu/chemistry/dgn/www/research/pcet.shtml). Wikipedia also has an article about Nocera (http://en.wikipedia.org/wiki/Daniel_G._Nocera) and he was picked as one of the Time 100 in 2009 (http://www.time.com/time/specials/packages/article/0,28804,1894410_1893209_1893470,00.html). YouTube video "The Artificial Leaf" (http://www.YouTube.com/watch?v=c-s_c6HjDwM) Daniel Nocera discusses the possibilities (3:46 min).

Donald Ort (http://www.life.illinois.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.

Greg Scholes (http://www.chem.utoronto.ca/staff/SCHOLES/scholes_home.html). The Scholes Group Research site covers quantum mechanics in photosynthesis energy transfer and nanoscale systems. It contains summaries of their work and links to journals and popular magazines that have featured their work. The lab's personnel section contains some cute personalized cartoons of the members.

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.

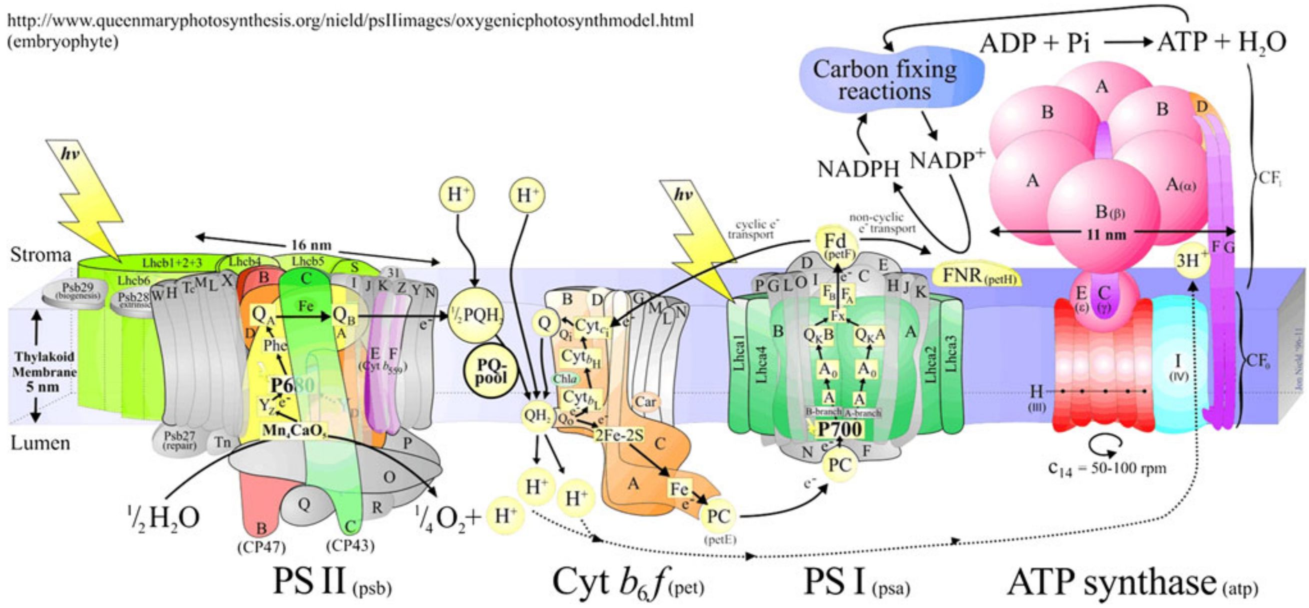

Fig. 13 The major protein structures from Jon Nield's site: http://macromol.sbcs.qmul.ac.uk/resources/AllComplexes_25Nov2011_1800px.gif

Elaine Tobin (http://www.mcdb.ucla.edu/Faculty/TOBIN/tobin.html). The theme here is phytochrome-regulated developmental processes, particularly of circadian clock in *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://bioenergy.asu.edu/faculty/vermaas). The theme is the molecular genetics of photosynthetic proteins. Wim studies structure, function and assembly of photosynthetic proteins by genetic engineering. You can read "An Introduction to Photosynthesis and its Application," published in World & I (http://bioenergy.asu.edu/photosyn/education/photointro.html). A YouTube video featuring Wim Vermaas discussing biofuels is available: http://www.YouTube.com/watch?v=WYAM0CIwUGI.

Elizabeth Vierling (https://sites.biochem.umass.edu/vierlinglab/). 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 passed away recently after 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 review. In August, 2004, he was presented the 1st Communication Award of the International Society of Photosynthesis Research for his outstanding efforts to help communicate information about photosynthesis to the general public. He is very much missed by all of us.

Michael R. Wasielewski (http://chemgroups.northwestern.edu/wasielewski). There is good information and links here for photo-induced electron transfer, artificial photosynthesis, and molecular electronics, among others.

Charles F. Yocum (http://labs.mcdb.lsa.umich.edu/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://labs.mcdb.lsa.umich.edu/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 that are primarily aimed towards 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.

We feel that it is important that all students (and their teachers) be aware of the complexity of the Internet and the Web pages that appear there. Perhaps one of the best tutorials on this is from the University of California, Berkeley (http://www.lib.berkeley.edu/TeachingLib/Guides/Internet/Evaluate.html). It is a very detailed article that helps users analyze Web pages and help determine which ones are more valid than others. It is a very important site!

Educational sites

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

A project by one of the authors (G) lists photosynthesis educational links at different levels (http://www.life.illinois.edu/govindjee/linksPSed.htm).

The Kahn Academy has posted a series of educational videos related to photosynthesis. See Fig. 14 for an example of a course. Mentioned earlier in the "Subject sites" section, they are repeated here:

Photosynthesis:

https://www.khanacademy.org/science/biology/photosynthesis/v/photosynthesis;

Photosynthesis: Light Reactions 1:

https://www.khanacademy.org/science/biology/photosynthesis/v/photosynthesis–light-reactions-1;

Photosynthesis: Light Reactions and Photophosphorylation:

https://www.khanacademy.org/science/biology/photosynthesis/v/photosynthesis—light-reactions-and-photophosphorylation;

Photosynthesis: Calvin Cycle:

https://www.khanacademy.org/science/biology/photosynthesis/v/photosynthesis—calvin-cycle;

Photorespiration:

https://www.khanacademy.org/science/biology/photosynthesis/v/photorespiration;

C-4 Photosynthesis:

https://www.khanacademy.org/science/biology/photosynthesis/v/c-4-photosynthesis;

CAM Plants:

https://www.khanacademy.org/science/biology/photosynthesis/v/cam-plants.

The Kahn Academy videos are also available on YouTube and are often embedded in other Web sites, a practice encouraged by the creator, Salman Khan.

Photosynthesis is used as an example in teaching science as a language. This article from Stanford News Service explains how teaching concepts using everyday words and then introducing complex terms such as "photosynthesis" may speed learning in some groups: http://news-ser

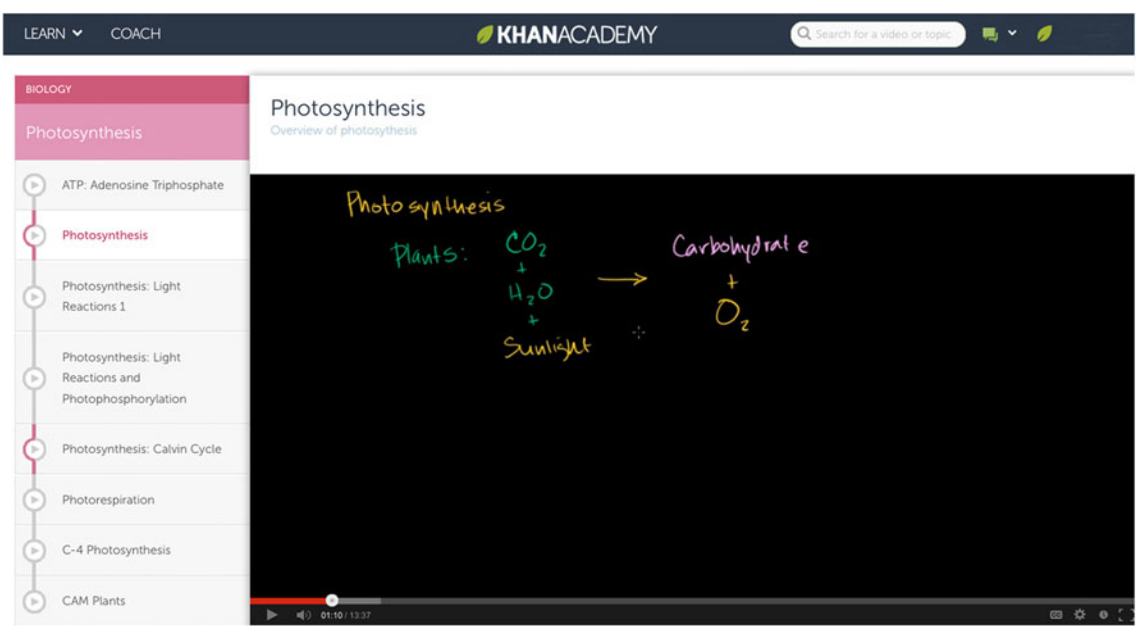

Fig. 14 The Khan Academy is pioneering online teaching. Pictured here is the start of lesson on "Photosynthesis" (https://www.khanacademy.org/science/biology/photosynthesis/v/photosynthesis) that will give the essentials in a friendly teacher-to-student format, much as done on an old-fashioned chalkboard. The student can replay any parts that are not understood upon first viewing. Teachers are able to track student progress and intervene if necessary

vice.stanford.edu/news/2008/august20/teachsci-082008.html.

Science and Plants for Schools (SAPS) (http://www.saps.org.uk/about-us) presents information for students regarding the importance of plants in the world. It is sponsored by the Cambridge University Botanic Garden, the University of Cambridge and others. It contains many items regarding photosynthesis and numerous outside links to experiments for students, including videos. It also includes "Photosynthesis—A Survival Guide for Teachers" (http://www.saps.org.uk/secondary/teaching-resources/134-photosynthesis-a-survival-guide-teaching-resources) with many useful Powerpoint modules.

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://bioenergy.asu.edu/photosyn/study.html).

Newton's Apple, a show that originally appeared on Public Broadcasting Service (PBS), 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).

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).

http://hdgc.epp.cmu.edu/teachersguide/teachersguide.htm is a "Teachers' Guide to High Quality Educational Materials on Climate Change and Global Warming." It also contains information about the climate change controversy and links to other sites.

The U.S. Energy Information Administration of the Department of Energy is responsible for "Energy Kids" (http://www.eia.doe.gov/kids). It contains good introductions to many solar energy subjects such as biomass, biofuels, hydrogen and non-biological energy. It also has links to games, calculators, puzzles. This is an excellent site for students and teachers to roam around in and has a number of solar energy lesson plans for teachers.

The Massachusetts Institute of Technology offers free courses in photosynthesis. "Photosynthesis: Life from Light" (http://ocw.mit.edu/courses/biology/7-343-photosynthesis-life-from-light-fall-2006) is an undergraduate-level course. The site links to all the necessary course materials, some of which are available directly online and PDFs that must be downloaded. Videos are available as iTunes links or YouTube videos. Note that the course is for personal education and review, no course credit is granted.

MIT also offers a link to MITnews arranged by subject matter. Here is the link to the section on photosynthesis: http://web.mit.edu/newsoffice/topic/photosynthesis.html.

For fun, we recommend the Z-Scheme videos by the Ohio State Football team. There are 2 versions: (A) is at http://www.YouTube.com/watch?v=XsZlPeT3D10&eurl= is version A; and B is at http://www.YouTube.com/watch?v=OnvuYLvInWE&mode=related&search=.

Lesson plans

Lesson plans posted at various schools often disappear at the end of the academic year. Please let Larry Orr (larry.orr@asu.edu) know if any lesson plan links are broken, moved, or if you know of any that are not listed. At the present time we are listing only free online lesson plans. There are many commercial educational companies offering high-quality lesson plans and materials, but they are beyond the scope of this paper.

"Photosynthesis" by Kelly Roe and Maureen Quessenberry can be found at http://earthref.org/SCC/lessons/2010/biogeochemistry/photosynthesis/. The lesson plan is intended for middle school students and includes links to PowerPoint notes. The activities are planned for 55 min periods over 3 days.

"Fun Photosynthesis" (http://www.beaconlearningcenter.com/Lessons/4266.htm) by Stephanie Callaway is a lesson plan that involves middle school students performing skits in which they learn about photosynthesis and act out the process using homemade props. This activity takes about 6 days and includes links to necessary materials and assessment files.

"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 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.

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

Nelida Boreale provides a lesson plan for "Photosynthesis and Transpiration" for grades 6–8 (http://www.cbv.ns.ca/sstudies/science/sci1.html).

National Geographic Xpeditions presents: "Photosynthesis, Trees, and the Greenhouse Effect" (http://www.nationalgeographic.com/xpeditions/lessons/08/g68/brainpopphoto.html).

Discovery Education features: "Yummy Plant Parts," a lesson plan that helps students understand plants and why they are important (http://www.discoveryeducation.com/teachers/free-lesson-plans/yummy-plant-parts.cfm).

From Wales, UK: "Plants need light and water to grow" (http://www.ngfl-cymru.org.uk/vtc/plants_light_water_to_grow/eng/Introduction/Default.htm). Contains easy interactive lessons, teachers' notes, and links to worksheets in MS Word format.

As mentioned previously, "Energy Kids" has a number of solar energy lesson plans organized by age groups (primary, elementary, intermediate and secondary) http://tonto.eia.doe.gov/kids/energy.cfm?page=Plans.

Proteacher.org lists a number of brief suggestions to aid in teaching elementary school students about photosynthesis (http://www.proteacher.org/c/947_Photosynthesis.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.

Julian Rubin has posted links to several of the historic experiments in "The Discovery of Photosynthesis" (http://www.juliantrubin.com/bigten/photosynthesisexperiments.html). He has also posted links to sites with possible science fair projects, organized by age group! (http://www.juliantrubin.com/fairprojects/botany/photosynthesis.html).

Science and Plants for Schools (SAPS) has a good experiment with a slide show for investigating photosynthesis using algal balls (http://www.saps.org.uk/secondary/teaching-resources/1224).

Other experiments of note are: "Investigating photosynthesis with leaf discs" (http://www.saps.org.uk/secondary/teaching-resources/284-investigating-photosynthesis-with-leaf-discs); "Measuring the rate of photosynthesis" (http://www.saps.org.uk/secondary/teaching-resources/157-measuring-the-rate-of-photosynthesis). A photosynthesis kit can also be ordered (http://www.saps.org.uk/secondary/teaching-resources/123-investigating-photosynthesis-with-the-saps-ncbe-photosynthesis-kit).

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), duplicating 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).

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 are to be made using carved sponges. Finally, students are to 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. 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.

"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; you juggle genes!. Just like in the lab, the student has to correctly perform the parts of the experiment or it fails (http://bioenergy.asu.edu/photosyn/education/experiments/protein_exp/cover.htm).

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

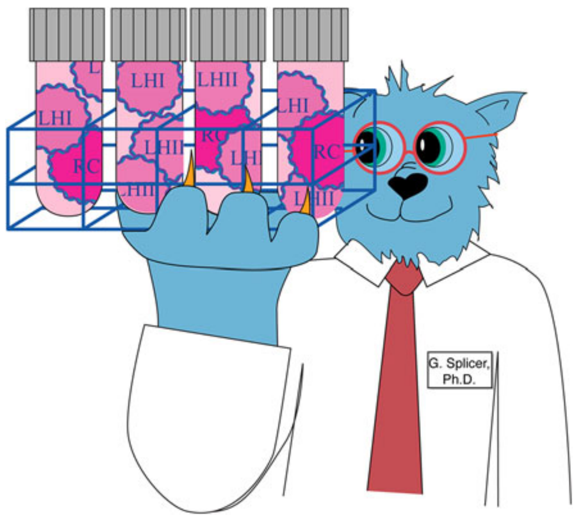

Fig. 15 Dr. Splicer prepares a virtual experiment at http://bioenergy.asu.edu/photosyn/education/experiments/protein_exp/cover.htm

A few videos of experiments are beginning to appear, though the quality is typically not very good. We hope that as more teachers become comfortable with video cameras and the Web they will post better experiments.

"Photosynthesis Syringe Experiment Year 8" shows oxygen production from discs cut from spinach leaves (http://www.YouTube.com/watch?v=MqutlhJ69IE) (you might want to turn off the distracting soundtrack!).

"Photosynthesis Under Water" (http://www.YouTube.com/watch?v=npFOKeH9hlU&feature=related) shows oxygen production controlled by light.

Knowledge/search sites, student and classroom videos/social networks

Knowledge/search sites are ever expanding sites dedicated to finding and publishing information about everything, not single subjects. They can be thought of online encyclopedias or a rudimentary *Hitchhiker's Guide to the Galaxy*.

Wikipedia: the Free Encyclopedia (http://en.wikipedia.org/wiki/Main_Page) is a great, and controversial, experiment in the communal creation and editing of a public reference source. It is now huge and is a major information source for students, teachers and the general public—even scientists! Its strengths are: it covers everything, especially modern cultural matters, but is also quite good at science and historical material in many areas; it is available in almost all modern languages. Its weaknesses are: lightness in the coverage of some areas; errors that are introduced by the public editors; bias in some of the articles; occasional hacks and deliberate misinformation being introduced temporarily until removed by others. On the whole it is a good source of information as long as the user is aware of its strengths and weaknesses. Both of the authors of this paper have participated in its creation and editing although others have often changed our entries, sometimes leading to frustration. Some good areas to check:

http://en.wikipedia.org/wiki/Photosynthesis
http://en.wikipedia.org/wiki/Photosystem_II
http://en.wikipedia.org/wiki/ATP_synthase
http://en.wikipedia.org/wiki/Chlorophyll
http://en.wikipedia.org/wiki/Global_warming [a hotspot for editorial controversies and discussion].

eHow (http://www.ehow.com/) advertises "How to do just about everything." It hires guest writers and videographers to provide answers to questions that it believes the public will ask. The answers are often interesting, if not very detailed, and may contain videos and links to other resources or references. Conversely, many of the presentations are quite elementary and would only be suitable for beginners. For example here are some photosynthesis related links from eHow:

"How Does Photosynthesis Work?" http://www.ehow.com/how-does_4623964_photosynthesis-work.html.

"How to Explain Photosynthesis" http://www.ehow.com/how_2251817_explain-photosynthesis.html.

"What is the Function of Photosynthesis?" A video: http://www.ehow.com/video_4753964_what-function-photosynthesis.html.

"What is the Function of Chlorophyll?" A video: http://www.ehow.com/video_4801944_what-function-chlorophyll.html.

Student and classroom videos can be found in many places on the Internet. The development of very inexpensive and small video cameras, including those built into cell phones and laptop computers have resulted in an explosion of non-professional videos on every imaginable subject. It did not take long before sites appeared to store and distribute the videos.

YouTube (http://YouTube.com) is by far the most famous of these sites. Throughout this review we have listed YouTube videos for individual subjects. YouTube allows the public to post comments to the videos and some of these may not be appropriate to all age groups. However, if monitored carefully, some YouTube videos may be helpful in teaching. Also, students can do their own video projects about their research and post these very easily to YouTube. Here are some videos about photosynthesis that are not listed elsewhere in this article. They may be fun to show students or possibly serve as inspiration to come up with similar (hopefully better) student projects.

"Glucose Song" (http://www.YouTube.com/watch?v=jJvAL-iiLnQ&feature=related) cute figures and clever lyrics.

"The Photosynthesis Song" by Peter Weatherall (http://www.YouTube.com/

watch?v=C1_uez5WX1o&feature=related) with nice animations. Peter Weatherall is an independent children's musician and animator who produces many CDs and DVDs filled with wonderful songs and cartoons about science. We recommend checking out his site for classroom ideas: http://kidsinglish.com/.

Another "Photosynthesis Song" sung by Mr. Durand, a teacher (http://www.YouTube.com/watch?v=_IV-E68rh18).

"Photosynthesis Rap" (http://www.YouTube.com/watch?v=q6XrL9uYJXo&feature=related) lacks production values but may get some classes involved.

"Cellular Respiration (ATP)—Boulevard of Broken Dreams" (http://www.YouTube.com/watch?v=hxTed-lTe7g) features bad singing (apologies to Green Day) with visual puns.

There are hundreds of similar presentations on YouTube and more being added all the time. To find others go to YouTube and enter your search in the search box.

TeacherTube is a lot like YouTube except it is run by an educational group and does not allow public postings or comments. Many schools have blocked YouTube, but allow TeacherTube. In general the videos are more limited, but of higher quality.

"Photosynthesis" (http://www.teachertube.com/viewVideo.php?video_id=62625&title=Photosynthesis) a rap with good figures.

"Photosynthesis Song" (http://www.teachertube.com/viewVideo.php?video_id=49549) the same video by Peter Weatherall that appears on YouTube.

"Lachman—Photosynthesis Respiration Song" (http://www.teachertube.com/viewVideo.php?video_id=134814) is a short cute video of an elementary classroom singing about photosynthesis.

"Photosynthesis Bioflix Animation" (http://www.blinkx.com/watch-video/photosynthesis-bioflix-animation/zWVQ8TsGQEG7FGsd2MWPTw) is commercially prepared and includes very good computer generated animations.

"Photosynthesis and Cell Respiration" (http://www.teachertube.com/viewVideo.php?video_id=158836&title=Photosynthesis_and_Cell_respiration) features animations with music by Linkin Park, "Shadow of the Day."

Use the search box in TeacherTube to find other videos.

Social networks are recent phenomena on the Web. Originally created to allow individuals, especially students, to communicate with each other, they are rapidly evolving into a major information source on the Internet. They are controversial and complex. For an article on the history, development, usefulness and risks, we recommend the Wikepedia article "Social Network Service" (http://en.wikipedia.org/wiki/Social_networking_service). Also see: "The Complete History of Social Networking—CBBS to Twitter" (http://www.maclife.com/article/feature/complete_history_social_networking_cbbs_twitter).

Facebook (http://www.facebook.com) started out as a network for college students, then later allowed anyone to join and publish sites. Now it is developing into a major communications site as special interest and corporate sites are added. At the present time there are few sites devoted to photosynthesis, but some have appeared:

The Facebook site for the ASU Center for Bioenergy & Photosynthesis (http://www.facebook.com/pages/Tempe-AZ/Center-for-Bioenergy-Photosynthesis/121720517379?ref=ts) is maintained by one of us (LO). See Fig. 16.

The Photosynthetic Antenna Research Center also maintains a dynamic Facebook site (https://www.facebook.com/WUParc). See Fig. 16.

The Climate Desk (http://www.facebook.com/theclimatedesk).

Steven Chu (http://www.facebook.com/stevenchu).

Twitter (http://twitter.com) is a micro-blogging site where people send out very small messages limited to 140 characters or less to people that subscribe to their site. Most messages were rather trivial personal statements, but it is now becoming a very popular means to deliver instant news about events. Some examples of photosynthesis sites are: ASU Center for Bioenergy & Photosynthesis (http://twitter.com/bioenergycenter) and Oliver Morton, author of Eating the Sun (http://twitter.com/Eaterofsun). Many small companies (and some large) are now using Twitter to send out announcements of products and miscellaneous postings that need to go out quickly. See Fig. 17.

Other useful sites

Books, journals and magazines

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—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 Web site will often contain the table of contents, abstracts,

Fig. 16 Facebook sites for the ASU Center for Bioenergy & Photosynthesis (*left*) (https://www.facebook.com/pages/Center-for-Bioenergy-Photosynthesis/121720517379?ref=ts) and the Photosynthetic Antenna Research Center at Washington University (*right*) (https://www.facebook.com/WUParc)

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. Checking an author's Web site for publication lists will reveal online access if the article shows up as a link. More articles are becoming available as funding agencies insist on public access to research funded by taxpayer money.

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. See Fig. 18. From volume 31 (2010), Thomas Sharkey has joined Govindjee as a co-series editor. Descriptions, free front matter and ordering information can be found at the Springer site (http://www.springer.com/series/5599); also see http://bioenergy.asu.edu/photosyn/books/advances.html (for volumes 1–18); (http://www.life.illinois.edu/govindjee/newbook/Vol19-25.html) for volumes 19–25; and http://www.life.illinois.edu/govindjee/g/References.html. The series currently contains 36 volumes with more in press and several in preparation. Published volumes are listed below (we list their Web site or, when available, Table of Contents and free downloadable Front Matter:

1. *The Molecular Biology of Cyanobacteria*—edited by Donald A. Bryant (http://www.springer.com/life+sciences/plant+sciences/book/978-0-7923-3222-0).
2. *Anoxygenic Photosynthetic Bacteria*—edited by Robert E. Blankenship, Michael T. Madigan, and Carl E. Bauer (http://www.springer.com/life+sciences/plant+sciences/book/978-0-7923-3681-5).
3. *Biophysical Techniques in Photosynthesis*—edited by Jan Amesz and Arnold J. Hoff. For downloading free Front Matter and to see Table of Contents:

Fig. 17 The Twitter site from the ASU Center for Bioenergy & Photosynthesis (https://twitter.com/bioenergycenter)

http://www.springerlink.com/content/978-0-7923-3642-6.

4. *Oxygenic Photosynthesis: The Light Reactions*—edited by Donald R. Ort and Charles F. Yocum (http://www.springer.com/life+sciences/plant+sciences/book/978-0-7923-3683-9).
5. *Photosynthesis and the Environment*—edited by Neil R. Baker. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-0-7923-4316-5.
6. *Lipids in Photosynthesis: Structure, Function and Genetics*—edited by Paul André Siegenthaler and Norio Murata. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-0-7923-5173-3.
7. *The Molecular Biology of Chloroplasts and Mitochondria in Chlamydomonas*—edited by Jean David Rochaix, Michel Goldschmidt-Clermont and Sabeeha Merchant. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-0-7923-5174-0.
8. *The Photochemistry of Carotenoids*—edited by Harry A. Frank, Andrew J. Young, George Britton and Richard J. Cogdell. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-0-7923-5942-5.

Fig. 18 Four books from the series *Advances in Photosynthesis and Respiration*. Series Editors: Volumes 1–30 (Govindjee); Volumes 31–present (Govindjee and Thomas Sharkey). See: http://www.springer.com/series/5599

9. *Photosynthesis: Physiology and Metabolism*—edited by Richard C. Leegood, Thomas D. Sharkey and Susanne von Caemmerer. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-0-7923-6143-5.
10. *Photosynthesis: Photobiochemistry and Photobiophysics*—authored by Bacon Ke. http://www.springer.com/life+sciences/plant+sciences/book/978-0-7923-6791-8.
11. *Regulation of Photosynthesis*—edited by Eva-Mari Aro and Bertil Andersson. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-0-7923-6332-3.
12. *Photosynthetic Nitrogen Assimilation and Associated Carbon and Respiratory Metabolism*—edited by Christine Foyer and Graham Noctor. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-0-7923-6336-1.

13. *Light-Harvesting Antennas in Photosynthesis*—edited by Beverley R. Green and William W. Parson: http://www.springer.com/life+sciences/plant+sciences/book/978-0-7923-6335-4.
14. *Photosynthesis in Algae*—edited by Anthony W. D. Larkum, S. E. Douglas and John A. Raven: http://www.springer.com/life+sciences/plant+sciences/book/978-0-7923-6333-0.
15. *Respiration in Archaea and Bacteria: Diversity of Prokaryotic Electron Transport Carriers*—edited by Davide Zannoni: http://www.springer.com/life+sciences/biochemistry+%26+biophysics/book/978-1-4020-2001-8.
16. *Respiration in Archaea and Bacteria: Diversity of Prokaryotic Respiratory Systems*—edited by Davide Zannoni: For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-1-4020-2002-5.
17. *Plant Mitochondria: From Genome to Function*—edited by David A. Day, A. Harvey Millar and James Whelan: http://www.springer.com/life+sciences/plant+sciences/book/978-1-4020-2399-6.
18. *Plant Respiration: From Cell to Ecosystem*—edited by Hans Lambers and Miquel Ribas-Carbo. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-1-4020-3588-3.
19. *Chlorophyll a Fluorescence: A Signature of Photosynthesis*—edited by George C. Papageorgiou and Govindjee. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-1-4020-3217-2.
20. *Discoveries in Photosynthesis*—edited by Govindjee, J. Thomas Beatty, Howard Gest and John F. Allen. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-1-4020-3323-0. This Web site shows the XVI sections of the book. To see all the historical papers, click on the roman numbers of each section. A unique thing about this book is that it lists, in a section called "In Memoriam", the birth and death years of a large number of past photosynthesis researchers, as of 2005; this list is included in the free downloadable Back Matter.
21. *Photoprotection, Photoinhibition, Gene Regulation and Environment*—edited by Barbara Demmig-Adams, William Adams III and Autar K. Mattoo. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-1-4020-3564-7.
22. *Photosystem II: The Light-Driven Water: Plastoquinone Oxidoreductase*—edited by Thomas J. Wydrzynski and Kimiyuki Satoh. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-1-4020-4249-2.
23. *Structure and Function of the Plastids*—edited by Robert Wise and J. Kenneth Hoober. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-1-4020-4060-3.
24. *Photosystem I: The Light-Driven Plastocyanin: Ferredoxin Oxidoreductase*—edited by John H. Golbeck. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-1-4020-4255-3.
25. *Chlorophylls and Bacteriochlorophylls: Biochemistry, Biophysics, Functions and Applications*—edited by Bernhard Grimm, Robert Porra, Wolfhart Rüdiger and Hugo Scheer. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-1-4020-4515-8.
26. *Biophysical Techniques in Photosynthesis II*—edited by Thijs J. Aartsma and Jörg Matysik. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-1-4020-8249-8.
27. *Sulfur Metabolism in Phototrophic Organisms*—edited by R. Hell, C. Dahl, D. B. Knaff and Th. Leustek. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-1-4020-6862-1.
28. *The Purple Phototrophic Bacteria*—edited by C. Neil Hunter, Fevzi Daldal, Marion C. Thurnauer and J. Thomas Beatty. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-1-4020-8814-8.
29. *Photosynthesis in Silico: Understanding Complexity from Molecules to Ecosystems*—edited by Agu Laisk, Ladislav Nedbal and Govindjee. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-1-4020-9236-7.
30. *Lipids in Photosynthesis*—edited by Hajime Wada and Norio Murata. For downloading free Front Matter and to see Table of Contents: http://www.springerlink.com/content/978-90-481-2862-4. [Note that beginning with this volume (30), all colored figures are within the chapters, and, thus, not available in the free downloadable Front Matter.]
31. *The Chloroplast*—edited by C. A. Rebeiz, C. Benning, H. J. Bohnert, H. Daniell, J. K. Hoober, H. K. Lichtenthaler, A. R. Portis and B. C. Tripathy: http://www.springer.com/life+sciences/plant+sciences/book/978-90-481-8530-6.
32. *C-4 Photosynthesis and Related CO_2 Concentrating Mechanisms*—edited by A. S. Raghavendra and R. F. Sage: http://www.springer.com/life+sciences/plant+sciences/book/978-90-481-9406-3.

33. *Functional Genomics and Evolution of Photosynthetic Systems*—edited by Robert Burnap and Wim Vermass: http://www.springer.com/life+sciences/book/978-94-007-1532-5.
34. *Photosynthesis: Plastid Biology, Energy Conversion and Carbon Assimilation*—edited by Julian Eaton-Rye, Baishnab C. Tripathy and Thomas D. Sharkey: http://www.springer.com/life+sciences/plant+sciences/book/978-94-007-1578-3.
35. *Genomics of Chloroplasts and Mitochondria*—edited by Ralph Bock and Volker Knoop: http://www.springer.com/life+sciences/plant+sciences/book/978-94-007-2919-3.
36. *Plastid Development in Leaves during Growth and Senescence*—edited by Basanti Biswal, Karin Krupinska and Udaya C. Biswal: http://www.springer.com/life+sciences/plant+sciences/book/978-94-007-5723-3

Other books of note are (we have taken the liberty of listing some specialty books as well):

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/Aquatic-Photosynthesis-Paul-G-Falkowski/dp/0691115516).

Artificial Photosynthesis: From Basic Biology to Industrial Application (2005), edited by Anthony F. Collings and Christa Critchley: http://www.wiley.com/WileyCDA/WileyTitle/productCd-3527310908.html.

Bioenergetic Processes of Cyanobacteria From Evolutionary Singularity to Ecological Diversity (2011), edited by G. A. Peschek, C. Obinger and G. Renger, is available at http://link.springer.com/book/10.1007/978-94-007-0388-9/page/1. This book has an important photosynthetic content.

C3, C4: Mechanisms and Cellular and Environmental Regulation of Photosynthesis (1983), by Gerald Edwards and David Walker. A digital edition is available for free download from: http://www.hansatech-instruments.com/forum/uploads/david_walker/c3c4.pdf. Also, copies are sometimes available on Amazon.com.

Concepts in Photobiology: Photosynthesis and Photomorphogenesis (1999), edited by Gauri S. Singhal, Gernot Renger, Sudhir K. Sopory, Klaus Dieter Irrgang and Govindjee (http://www.amazon.com/Concepts-Photobiology-Photomorphogenesis-G-S-Singhal/dp/0792355199).

Eaarth: Making a Life on a Tough New Planet (2010), by Bill McKibben, published by Times Books. McKibben, a well-known and popular environmental writer, writes from the point-of-view that climate change has already started and cannot be contained. The author does manage to maintain a positive outlook despite the problems caused by the projected climate change: http://us.macmillan.com/eaarth.

Eating the Sun: How Plants Power the Planet (2004), by Oliver Morton, published by Fourth State. It is a 'must' reading for all, even those only remotely interested in Photosynthesis. It is available from Amazon.com and other sources. His blog for the book is Heliophage and can be found at: http://heliophage.wordpress.com/ and his Twitter site is http://twitter.com/Eaterofsun. See additional information at http://bioenergy.asu.edu/CB&P/Books/Eating-the-Sun.html.

Energy Transduction in Biological Membranes. A Textbook of Bioenergetics (1989), by William A. Cramer and David B. Knaff. See a book review by B. A. Barry at: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1275687/pdf/biophysj00080-0270.pdf. It is a thorough textbook that all graduate students must read.

Membrane Biophysics (2000), by H. Ti Tien and Angelica Ottova-Leitmannova. It was published by Elsevier and complete details are available at: http://www.msu.edu/user/ottova/membrane.biophysics.html.

Molecular Mechanisms of Photosynthesis (2002), by Robert E. Blankenship. Available at: http://www.amazon.com/Molecular-Mechanisms-Photosynthesis-Robert-Blankenship/dp/0632043210. It is a Wiley-Blackwell book: 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 Solar Fuels (RSC Energy and Environment Series) (2011), edited by Thomas J. Wydrzynski and Warwick Hillier, is found at http://www.rsc.org/Shop/books/2011/9781849730341.asp. The book points out that "World demand for energy is rapidly increasing and is projected to more than double by the year 2050. Finding sufficient supplies of clean energy for the future is one of the major scientific challenges of today." This book deals very well with this topic.

Molecular to Global Photosynthesis (2004), edited by Mary D. Archer and James Barber. See: http://www.icpress.co.uk/lifesci/p218.html.

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 Table of Contents at the following Website: http://www.springerlink.com/content/978-0-387-72654-0.

Photosynthesis, 6th Edition (1999), by David O. Hall and Krishna K. Rao has gone through several editions and is still one of the best entry-level 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 simple 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-Dr-David-Lawlor/dp/1859961576.

Photosynthesis: A Comprehensive Treatise (1998), edited by Agepati S. Raghavendra, is found at http://www.cambridge.org/us/catalogue/catalogue.asp?isbn=9780521570008 (Cambridge Press).

Photosynthesis Research Protocols (2004), edited by Robert Carpentier. It is available at Amazon.com (http://www.amazon.com/exec/obidos/ASIN/1588292320/gemotrack8-20). Also see: http://www.springerprotocols.com/BookToc/doi/10.1385/1592597998.

Photosynthetic Excitons (2000), 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) (1997), by A. Wild and R. Ball (http://www.springerlink.com/content/u821771872363212/) (Buckuys Publishers). Its ISBN is: 90-73348-70-6.

Plant Biochemistry and Molecular Biology (1997), 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 (Oxford University Press).

Primary Processes of Photosynthesis: Principles and Apparatus (2008), edited by Gernot Renger, is an excellent book that deals with the very first steps of photosynthesis; it is available at Amazon.com (http://www.amazon.com/Primary-Processes-Photosynthesis-Comprehensive-Photobiological/dp/0854043640). See Govindjee (2010) Photosynthesis Research 103: 161–163, for a detailed review.

Probing Photosynthesis: Mechanism, Regulation & Adaptation (2000), edited by Mohammad Yunus, Uday Pathre and Prasanna Mohanty (http://www.amazon.com/Probing-Photosynthesis-Mechanism-Regulation-Adaptation/dp/0748408215). See: http://bioenergy.asu.edu/photosyn/books/probebk.html.

Stress Biology of Cyanobacteria: Molecular Mechanisms to Cellular Processes (2013), edited by A. K. Srivastava, A. N. Rai and B. A. Neilan, has important photosynthesis content, and since cyanobacteria, like algae, are important for Bioenergy, we list this volume as an important addition to the field. See http://www.crcpress.com/product/isbn/9781466504783.

Sustainable Energy—Without the Hot Air, by David J. C. MacKay, is a highly recommended book that covers sustainable energy in a straightforward, non-sensational manner (hence, without hot air); one section is titled, "Numbers, not adjectives," to indicate that science is more important than political hype. It is available as a paperback book, a free downloadable PDF file, and even chapter-by-chapter on the Web. There are even Kindle and epub versions for digital readers. Access is at: http://www.withouthotair.com/.

The Photosynthetic Membrane: Molecular Mechanisms and Biophysics of Light Harvesting (2012), by A. Ruban, Wiley-Blackwell, Chichester, is a welcome addition to the field of photosynthesis; see http://queenmaryphotosynthesis.org/~ruban/news.htm.

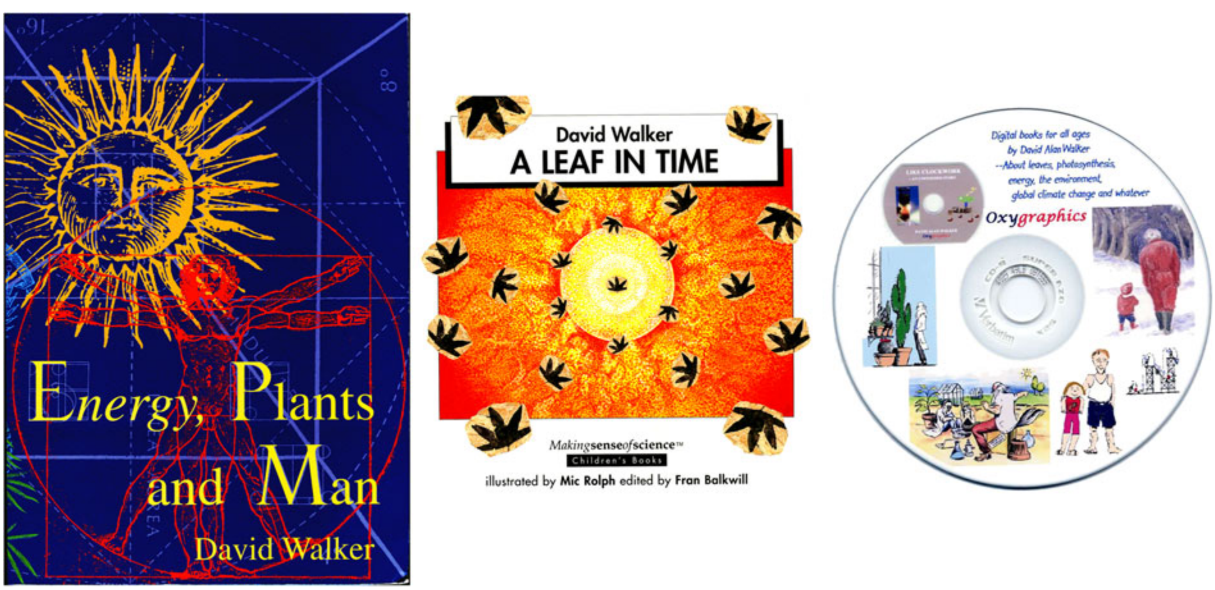

Fig. 19 Some of the great books written by David Walker

Before he passed away, David Walker produced a wonderful set of books that approach photosynthesis from several different angles and which are written for several age groups. See Fig. 19. Most are available as free downloads (in accord with the principle of fair-use) from Hansatech Instruments and the International Society of Photosynthesis Research (ISPR).

1. *Energy, Plants and Man*: http://www.hansatech-instruments.com/forum/uploads/david_walker/Energy,Plants%20and%20Man.pdf.
2. *Global Climate Change*: http://www.hansatech-instruments.com/forum/uploads/david_walker/Global%20Climate%20Change.pdf.
3. *A Leaf in Time:* http://www.hansatech-instruments.com/forum/uploads/david_walker/A%20Leaf%20in%20Time.pdf. A Spanish version, "Una Hoja a Través del Tiempo" is also available: http://www.hansatech-instruments.com/forum/uploads/david_walker/Una%20hoja%20a%20traves%20del%20tiempo.pdf.
4. *Like Clockwork*: http://www.hansatech-instruments.com/forum/uploads/david_walker/Like%20Clockwork.pdf.
5. *A New Leaf in Time*: http://www.hansatech-instruments.com/forum/uploads/david_walker/A%20New%20Leaf%20in%20Time.pdf.
6. *Use of the Oxygen Electrode*: http://www.hansatech-instruments.com/forum/uploads/david_walker/use_of.pdf.

Our favorites are: *A Leaf in Time* (for ages 8–12) which discusses photosynthesis and its relationship to energy, plants and people; *A New Leaf in Time* (much longer, in PDF format only and with copious hyperlinks, for ages 9–99); *Energy, Plants and Man*, a large, profusely illustrated book with a great deal of information presented in an uncomplicated and humorous manner and is perfect for the classroom (high school, early college) or for just plain enjoyable reading. *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. The International Society for Photosynthesis Research and Hansatech company have also made his works available in PDF format at http://www.hansatech-instruments.com/books.htm.

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

Links to older volumes and books intended for young readers and the general public can be found at http://bioenergy.asu.edu/photosyn/books.html.

Scholarly journals

The following journals are peer-reviewed journals with established credentials. There has been a plethora of recently announced open-access scientific journals. Some of these are peer-reviewed, but many are not and may be defined as vanity journals with little editorial oversight. Until the field has settled, we will only list confirmed peer-reviewed journals.

Archives of Microbiology (http://link.springer.de/link/service/journals/00203/)
Functional Plant Biology (http://www.publish.csiro.au/?nid=102).
Biochemistry (http://pubs.acs.org/journal/bichaw)
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)
Biophysical Journal (http://www.cell.com/biophysj/)
Cell (http://www.cell.com/)
FEBS Letters (http://www.febsletters.org/)
Journal of American Chemical Society (JACS) (http://pubs.acs.org/journal/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/chemistry/physical+chemistry/journal/10822)
Journal of Photochemistry and Photobiology B: Biology (JPP) (http://www.journals.elsevier.com/journal-of-photochemistry-and-photobiology-b-biology/)
Journal of Physical Chemistry A (http://pubs.acs.org/journal/jpcafh)
Journal of Physical Chemistry B (http://pubs.acs.org/journal/jpcbfk)
Journal of Physical Chemistry C (http://pubs.acs.org/journal/jpccck)
Nature (http://www.nature.com/nature/index.html)
Photochemistry and Photobiology (http://onlinelibrary.wiley.com/journal/10.1111/%28ISSN%291751-1097)
Photosynthesis Research (http://www.springerlink.com/content/1573-5079/) the official journal of the International Society of Photosynthesis Research (ISPR) (http://photosynthesis-research.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) (PNAS) (http://www.pnas.org/)
Protein Science (http://www.proteinscience.org/)
Science (http://www.sciencemag.org/)

Magazines of interest to the general public

COSMOS (http://www.cosmosmagazine.com/)

Current Science (http://www.weeklyreader.com/archive/35) (grades 6–10)
Discover (http://discovermagazine.com/)
E Magazine (http://www.emagazine.com/)
Environment (http://www.environmentmagazine.org/)
Grist (http://www.grist.org/)
National Geographic (http://ngm.nationalgeographic.com/)
National Wildlife (http://www.nwf.org/News-and-Magazines/National-Wildlife.aspx)
New Scientist (http://www.newscientist.com/)
Orion (http://www.orionmagazine.org/)
Physics Today (http://www.physicstoday.org/)
Popular Mechanics (http://www.popularmechanics.com/)
Popular Science (http://www.popsci.com/)
Science Illustrated (http://www.scienceillustrated.com/)
Science News (http://www.sciencenews.org/)
Scientific American (http://www.scientificamerican.com/)
Seed (http://seedmagazine.com/)
Smithsonian (http://www.smithsonianmag.com/)
Wired (http://www.wired.com/)
World and I (http://www.worldandi.com/)
Yes! (http://www.yesmagazine.org/)

Societies and organizations

Some selected ones are listed below:

ISPR—International Society of Photosynthesis Research (http://photosynthesis-research.org) For only $80 (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 a discount on all books in the *Advances in Photosynthesis and Respiration* series published by Springer (http://www.springer.com/series/5599?detailsPage=titles).

American Chemical Society: http://portal.acs.org/portal/acs/corg/content
American Society for Horticultural Science: http://www.ashs.org/
ASP—American Society for Photobiology: http://www.photobiology.org/
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/
World Watch Institute: http://www.worldwatch.org/, presents information on many important issues, including climate change, environmental and energy matters.

Databases and genome projects

A Wikipedia article on biological databases lists many useful links: http://en.wikipedia.org/wiki/List_of_biological_databases
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
Genome: http://www.ncbi.nlm.nih.gov/genome
Protein Data Bank (PDB): http://www.rcsb.org/pdb/home/home.do
Rhodobacter sphaeroides genome project: http://www.rhodobacter.org

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. These are provided as a service and no endorsement is implied.

Agrisera: http://www.agrisera.com/en/artiklar/plant_algal-cell-biology/photosynthesis-/index.html
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/
Dynamax: http://www.dynamax.com/
EARS—Environmental Analysis and Remote Sensing: http://www.ears.nl
Fisher Scientific: http://www.fishersci.com
Hansatech Instruments: http://www.hansatech-instruments.com/. We want to commend Hansatch for making most of David Walker's publications available at http://www.hansatech-instruments.com/david_walker.htm
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: http://www.psi.cz/

Fig. 20 The authors. *Left* Govindjee in Jaipur, India. *Right* Larry Orr at Arizona State University

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

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

We end this review with photographs of the authors (see Fig. 20).

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