Photosynthesis *in Silico*: A multimedia CD-ROM combining animations, simulations and self-paced modules for photosynthesis education at all tertiary levels

Sharon A. Robinson, Wendy Russell and Andrew Netherwood
Department of Biological Sciences, University of Wollongong, Wollongong, NSW 2522, Australia

Introduction

Photosynthesis is a vital component of any undergraduate biology course. Despite its central importance in providing biochemical energy, fixed carbon and oxygen for all life on Earth, it remains an area which students find uninteresting and difficult to comprehend. This difficulty is compounded by problems with laboratory equipment for practical classes, which tends to be either expensive and complex, or simple and unreliable, making it extremely difficult to provide effective, hands-on teaching of photosynthesis to the large class sizes in undergraduate biology courses.

A set of interactive, multimedia modules have been combined on a CD-ROM, which provides a new approach to university teaching of photosynthesis. Features include animations of the photosynthetic electron transport process, serving both as an introduction to experimental exercises and as stand-alone material for use in undergraduate lectures or tutorials, and simulated experimental models of photosynthetic gas exchange and chlorophyll fluorescence which can be used either as stand-alone packages or, where equipment is available, to supplement and enrich a laboratory demonstration/experiment. These provide students with access to the latest experimental techniques and theory, providing an experience and knowledge base that facilitates understanding of the subject in greater depth.

The challenges of photosynthesis education

Photosynthesis raises a number of challenges for teachers. Plant science is, in general, under-represented in high school and undergraduate courses (Hershey 1992), and often receives a poor response, especially from students enrolled in biomedical type courses (who cry 'plants are boring'). Aware of the central role of this process in biology, teachers struggle, nevertheless, to promote the relevance and importance of photosynthesis to their students. Photosynthesis is also a conceptually difficult topic, which spans several disciplines (biophysics, biochemistry, ecophysiology) and organisational levels (molecules, cells, organisms, ecosystems). Because of these problems of relevance and difficulty, major misconceptions often persist in students' understanding of photosynthesis. In addition to these major misconceptions, students may become familiar with words and descriptions of processes such as electron transport, light harvesting, oxygen evolution and carbon fixation, but may have only a very shallow, and in some cases, flawed understanding of what these processes really are. Although they may be able to develop these concepts sufficiently to pass examinations at lower educational levels, their 'literacy' in this area is likely to remain at a low level (Uno and Bybee 1994), and they may have to 'unlearn' and relearn this material at higher levels, as flaws in their understanding begin to compromise their progress in this area.

There is clearly a need for new teaching materials and approaches that present photosynthesis in all its complexity, but in a way that stimulates the interest and excitement of students, and promotes deep and accurate understanding. Multimedia has the potential, in combining written and spoken word with dynamic pictures and models, to bring abstract concepts and invisible objects and processes to life, and to do so in a flexible and reliable way which increases retention and learning (Moore and Miller 1996). This paper presents a new teaching aid that uses multimedia to enhance teaching and learning of the light reactions of photosynthesis.

Content of the CD-ROM

The CD-ROM is designed as a series of five modules (Table 1). Modules 1 and 5 contain four experimental scenarios, in which students conduct simulated experimental procedures, and collect and analyze data. These require virtually the same level of involvement and understanding from students as the experiments they simulate, while ensuring that a consistent practical outcome is achievable by all students, even in large classes, and that theoretical aspects are not obscured because of technical problems. Modules 2-4 (Table 1) cover theory in areas at the forefront of research that are not well described in the available texts, are conceptually difficulty for students and/or are better illustrated through animation. Animations and dynamic links between text and figures make the modules attractive and visually stimulating, and also clarify and reinforce concepts. All modules include an extensive, up-to-date list of references. The modules are all interactive, providing flexibility to students in the pace, depth, and sequence in which they complete material in the modules, in or out of class time.

Module #	Topic	Target audience*
1	Oxygen evolution by *Egeria* (2 modules)	
	a) Effect of light quality on photosynthesis	1st Year
	b) Effect of light quantity on photosynthesis in sun and shade leaves	2nd Year
2	Plant adaptations to sun and shade	2nd Year
3	The photosynthetic electron transport chain	2nd Year
4	How do plants cope with excess light?	3rd Year
5	Measuring photosynthesis using chlorophyll fluorescence	3rd Year

Table 1. The five modules of the Photosynthesis *in Silico* CD-ROM, showing topics and target audience.

***The target audiences are given as years where these modules are currently in use at the University of Wollongong.**

Module 1 - Oxygen evolution by *Egeria*

The first part of this module was first designed to replace a first year practical within a biochemistry and cell biology course where students study the effects of light of different wavelengths on photosynthesis in the aquatic plant *Egeria*. The experiment is a very elegant demonstration of a key concept in photosynthesis but the practicality of running it in large introductory classes was a nightmare. The results were extremely unreliable, often the opposite to that expected and were a poor introduction to the complex process of photosynthesis. With practical classes of 80 students (400 total enrolment) the solution has been the production of a simulation to replace this practical. A screen shot is shown in Figure 1.

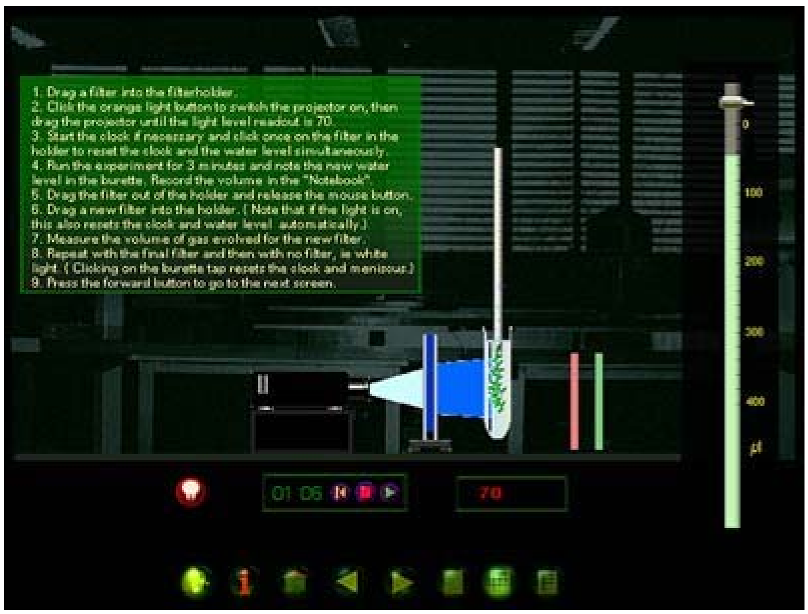

Figure 1. Screen shot of the O_2 evolution by *Egeria* experimental simulation from Module 1a

The second simulation in this module considers the effect of light quantity on the rate of O_2 evolution. Students can use plants collected from the surface of the pond (sun plants) or from deeper water (shade plants). By altering the amount of light incident on the plants, the students can investigate the light levels at which the photosynthetic rate is saturated and are introduced to the concept of light response curves. Since variation is built into the results students working in groups can produce a set of 'replicated' data from which they can calculate means and standard deviations. Module 2 contains complementary material for this second simulation, allowing students to understand the theoretical aspects of plant adaptation to various light levels.

Module 3 - Photosynthetic electron transport animation

One of the fundamental challenges of teaching in areas such as biochemistry and biophysics is that learning in these areas involves the comprehension of objects and processes that can't be seen or experienced. As scientists, we learn about things like proteins, membranes, electron transport and light harvesting from indirect observations, using measuring systems and analytical methodologies of various sorts. Knowledge about the nature of these invisible entities evolves, punctuated by controversy and consensus about the actual structures and the characteristics that define them. Regardless of the sophistication of our understanding, and its fit with empirical data, we visualise these objects and processes using imagination, models and metaphors. Our challenge in teaching is to communicate our vision of objects and processes in such a way that we generate understanding and excitement while avoiding misconception.

We have taken a biological process that is complex, conceptually difficult, and a traditional source of confusion and misunderstanding in the classroom. Photosynthetic electron transport, even more than respiratory electron transport, involves understanding of diverse areas, including photophysics, redox chemistry, enzymology and membrane biophysics. Even to set the stage, students must conceptualise the thylakoid membrane, protein complexes embedded in this membrane and electron transport components bound to these proteins. Add to this the dynamic, multi-step processes of light harvesting, electron transport, proton pumping, and photophosphorylation, and it is not surprising that this area is an educational challenge.

We have presented photosynthetic electron transport as a 4-dimensional animation (Figure 2), which combines up-to-date information about structure and function with attractive and exciting visual effects, which we hope will enhance understanding, interest and recall. The animation avoids over-simplification and shows features such as electron gating in PSII, the Q cycle of the cytochrome b6f complex, and the binding change mechanism of the ATP synthase (Figure 3). The entire chain is presented as four separate animations which students can explore at their own pace, with or without descriptive voice-over. The animations have been composed from a single panoramic view of the entire chain, and each animation, and the events associated with each protein complex, are clearly linked, so that connections and an integrated understanding of the chain can be gained. The animation is augmented by short descriptions of the complexes and electron transport components that can be viewed by students at any point as they work through the animations. There are also several introductory pages of text. In bringing together excellent graphic design expertise and software with the inside knowledge of active researchers in the area, the module presents an imaginative and sophisticated view of this key process to students at all levels of tertiary education.

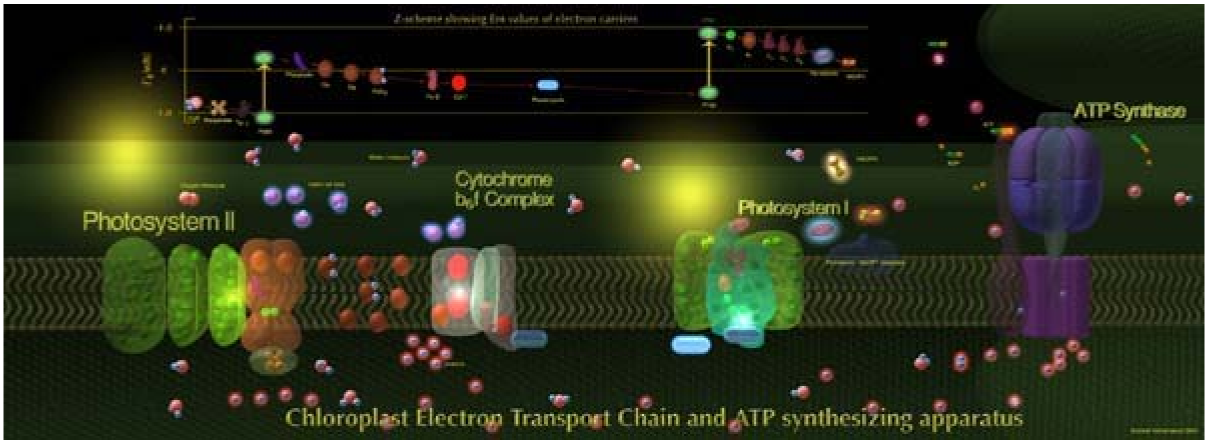

Figure 2. Screen shot of the photosynthetic electron transport chain, ATP synthase and Z-scheme from Module 3

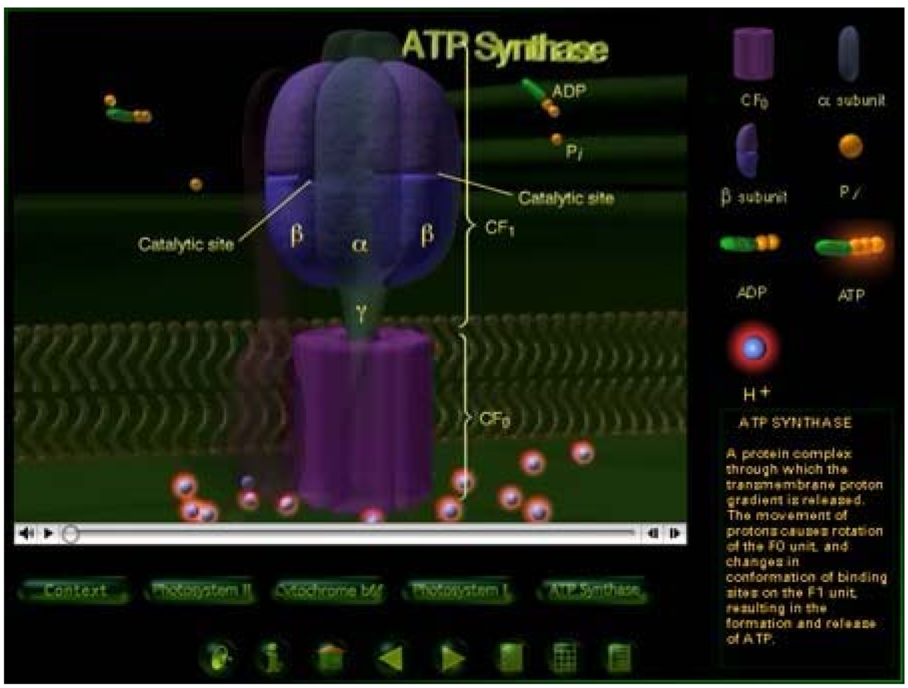

Figure 3. Screen shot of the photosynthetic electron transport chain, ATP synthase and Z-scheme from Module 3

Module 5 - Measuring photosynthesis using chlorophyll fluorescence

A major aim of the whole project was to increase understanding of core photosynthetic principles in introductory level biology and to allow senior students to meaningfully interact with experimental simulations to facilitate understanding of equipment used in project work and in the wider world of scientific research. Module 5 is used to supplement a third year plant ecophysiology practical class where the students are introduced to techniques that they will use in a project later in the course. The module explains the theoretical basis underlying the use of chlorophyll fluorescence and also provides two experimental simulations where the students determine the effect of increasing light levels on photosynthetic electron transport rate or the induction of photosynthesis in a leaf. The fluorescence module is also very useful as an introduction to chlorophyll fluorescence for students entering postgraduate research projects. The fluorescence module has been successfully used at third year level for the past five years. Prior to its use, traditional delivery by lecture and practical to classes of up to 50 students was very unproductive. Testing of students (by examination and practical report writing) showed that the key concepts were poorly understood and students had difficulty relating to the practical objectives. Since the modules have been employed, student reports have demonstrated improved understanding of the basic concepts and in examinations, students are self selecting essay questions relating to this module which previously were avoided. The quality of the examination responses is also much improved. Over the past three years the mean mark for short answer questions containing material which was only covered in lectures was 43%, whereas with material that was fully supported by the modules, the mean increased significantly to 75% (Analysis of Variance, $F_{2,136} = 11.89$, $P<0.0001$). Module 4, which covers the response of plants to excess light stress, contains theoretical material to complement the fluorescence module.

Conclusion

This CD-ROM provides valuable resources for teaching the fascinating and fundamental process of photosynthesis. It can be used to augment lectures and tutorials; as an adjunct to experimental work, or as stand-alone, self-paced modules in practical classes; and as a flexibly delivered course component. A key outcome of the project is that it ensures a consistent practical outcome to all students, regardless of class size. In large practical classes, learning outcomes are affected by the quality of demonstration and the success of a particular experiment. This can result in variability within and between practical classes in any cohort. The great advantage of these experimental modules is that the practical outcome is determined by the programmers and although we have incorporated variation, as befits biological experimentation, it is not so great as to obscure the message.

Technical aspects

The modules were designed using *Macromedia Director* and will run on almost any Mac (not OS X) or PC capable of running *QuickTime* (version 5 or 6). Some of the modules are also suitable for web-based delivery.

Acknowledgements

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References

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Sharon A. Robinson
Department of Biological Sciences
University of Wollongong
Wollongong
NSW 2522
Australia
sharonr@uow.edu.au

Wendy Russell
Department of Biological Sciences
University of Wollongong
Wollongong
NSW 2522
Australia
wendyr@uow.edu.au

Andrew Netherwood
Department of Biological Sciences
University of Wollongong
Wollongong
NSW 2522
Australia

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