Practical

Modelling Photosynthesis to Increase Conceptual Understanding

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Biology students in their first year at university have difficulty understanding the abstract concepts of photosynthesis. The traditional didactic lecture followed by practical exercises that show various macroscopic aspects of photosynthesis often do not help the students visualise or understand the submicroscopic (molecular-level) reactions that are occurring within the chloroplast membranes. If students can construct their own complex concepts in small steps, with guidance from lecturers and demonstrators (teaching assistants) to ensure they are not building-in 'new' misconceptions, they are more likely to form positive attitudes towards further study and raise their self-esteem about learning strategies. This paper describes a teaching/re-teaching sequence of the light-dependent reactions of photosynthesis that presents the students with a range of learning and teaching approaches. Following a traditional didactic lecture, students have a practical exercise where they make their own models of chloroplasts, reinforced by small-group discussion sessions where they make their own diagrammatic summary. Online resources and textbooks are available for private study. The re-teaching step is an interactive lecture appealing to a range of learning modalities. Using this teaching and learning strategy, students increasingly use metacognitive skills to aid their further understanding of the submicroscopic world of atoms and molecules.
Keywords: Photosynthesis; Active learning; Submicroscopic concepts

Introduction

In biology, photosynthesis and cell metabolism have been identified as important, yet conceptually difficult areas (Stavy *et al*, 1987). The literature on 'misconceptions' or 'alternative frameworks' documents the difficulties that many students have in understanding these concepts (Stavy *et al*, 1987; Wandersee *et al*, 1994). Often these misconceptions have developed from previous learning experiences which may be personal in nature, show incomplete and contradictory understanding and these can be very stable and highly resistant to change (Driver and Bell 1986; Wandersee *et al*, 1994). Unsurprisingly, some teachers and textbook authors often subscribe to the same alternative conceptions and misconceptions as their students, perhaps partly because they have been subjected to similar teaching regimes (Wandersee *et al*, 1994).

Traditionally, a learning and teaching sequence on photosynthesis in tertiary education couples a didactic lecture with a practical class (Hodson 1998). Common practical exercises to demonstrate photosynthesis concepts range from simple experiments on aquatic plants to isolating chloroplasts from spinach and using them to demonstrate the light reactions of photosynthesis (the Hill reaction). Placing *Elodea* in an inverted filter funnel in an effort to observe bubbles from the leaf surface is a classic demonstration of the generation of oxygen by plants in the light. The oxygen collected is then tested with a glowing splint.

At a higher cognitive level, chloroplasts can be isolated and a reaction viewed using the disappearance of DCPIP (a dye that changes colour during oxidation/reduction reactions). Most students fail to connect the change in colour of the dye – as a result of consumption of electrons derived from water – with the bubbles of oxygen appearing on the leaf of the *Elodea* plant. Similarly, the submicroscopic concepts within photosynthesis cannot be demonstrated to students without specialised instruments which, even if available, would provide a limited contribution to conceptual development in an undergraduate student.

Additionally, a critical problem is that many students have very limited understanding of chemistry. For example, although the light reactions of photosynthesis can be measured using a fluorimeter, such an instrument is not comprehensible to a student who does not understand fluorescence, the quantum nature of light or how the experimental results relate to the underlying molecular concepts. Similarly, demonstrating with a pH meter that isolated thylacoids from chloroplasts can generate a pH gradient across the thylacoid membrane is not useful if the student only vaguely understands concepts of protons, acid/base reactions or pH.

Many educationalists (eg. Harrison and Treagust, 2002) have also questioned the usefulness of such practical exercises in deepening understanding of concepts, particularly those which try to relate a macroscopic response (e.g. in this case the bubbles of gas from the plant or chloroplast preparation) with an abstract, submicroscopic explanation (e.g. splitting of water to produce oxygen).

Instructional approaches that are designed to facilitate conceptual change and which rely on conceptual conflict, analogies and metacognitive strategies, have been shown to assist students in the transition toward scientifically acceptable understandings of natural phenomena (Wandersee *et al*, 1994; Gunstone 1995). Current research also suggests that, as many concepts required to understand scientific phenomena (such as photosynthesis) are counter-intuitive and abstract, the incorporation of a range of different modalities of learning may help students develop deeper understanding (Ross and Tronson 2004).

This paper focuses on a novel approach to the teaching of the light cycle of photosynthesis to promote conceptual ('deep') understanding rather than a 'strategic' or 'surface' learning approach (Biggs, 2003). The intention behind the development of these strategies is to supplement rather than replace traditional activities as described above. Model building using easily obtained 'everyday' materials is one way by which students can physically construct and manipulate their own representations of a given concept; it has been suggested as one intervention strategy which may develop cognitive-affective relationships (Wandersee *et al*, 1994). This approach has also been advocated in teaching particulate theory in chemistry (Harrison and Treagust, 2002, and references therein). With this in mind, this study describes a teaching sequence developed with the aim of modifying students' conceptual understanding of the light cycle of photosynthesis and, through this, of developing positive attitudes towards submicroscopic (molecular-level) concepts.

Methodology

Step 1. The Lecture

The first step in this teaching and learning sequence commenced with a traditional didactic lecture covering the light-dependent and light-independent reactions of photosynthesis, including the structure and function of chloroplasts within the plant body. The teaching strategy was mainly auditory in its focus with accompanying visual material in the form of a detailed Powerpoint presentation and animations (Figure 1). Students were also able to access the information given in the lectures and supplementary material on a dedicated website using Web CT. Specific references to a range of textbooks (our recommended textbook was Campbell and Reece, 2005) and a CD-ROM produced at the University of Western Sydney were also given.

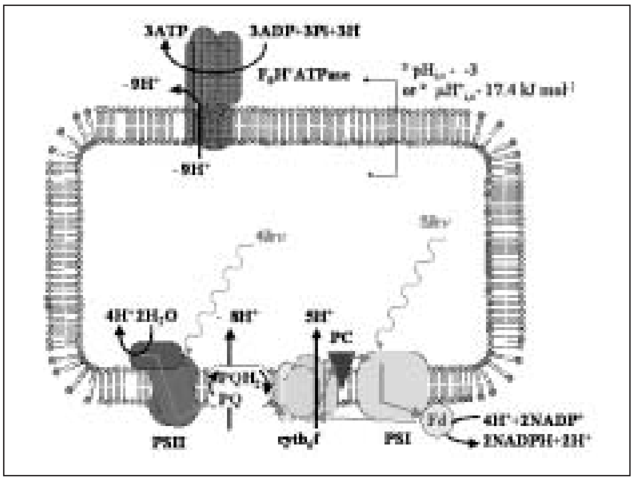
Step 2a. Making a Model Chloroplast

The practical class followed the lecture. Students were asked to make a model chloroplast. They were provided with some equipment having specific functions (see Appendix 1). The thylacoid membranes and granum were paper plates. Photosystems II were dark green sponges, while Photosystems I were yellow sponges. Chlorophyll molecules were represented by green crepe paper that was cut into the shape of chlorophyll molecules (head and long tail) and inserted into grooves in the sponges. ATP synthase was a push board pin that could be pushed through a paper plate and secured in place for safety with a cork. $NADP^+$ reductase was a coloured thumbtack. The inner and outer membranes were represented by clear plastic bags, while the H^+ ions were printed on a piece of paper. The electron transport chain was created from string and beads.

Students were questioned on how they could represent the stroma. The oxygen-evolving complex was also drawn on a piece of paper and attached to Photosystem II, along with H^+ ions that can be removed from the complex, so that students could represent the submicroscopic (atomic/molecular-scale) aspects of the 'splitting' of water and the production of molecular oxygen.

Once these pieces have been provided, the students were left to build the model, working in small groups. Throughout the process, the demonstrators (teaching assistants) guided the students by listening to the dialogue of the group and interacting when appropriate to challenge, confront or confirm students' developing concepts. Some examples of these chloroplasts are shown in Figure 2.

Figure 1. Diagram modified from Campbell and Reece (2005) of the processes within the thylacoid membrane in the light dependent stage of photosynthesis – an example of visual material used within the didactic lecture (Step 1).



Step 2b. Drawing the Model (a visual approach)

Students were then asked to draw their conceptions of a chloroplast and the processes of the light-dependent stage of photosynthesis on a A3 piece of paper, based on the model constructed in Step 2a (an example is shown in Figure 3).

Step 3. A Role-play within a Lecture

After this 'traditional' lecture and 'novel' practical, the concepts of photosynthesis were re-taught within an interactive lecture using role-play and concept diagrams (Novak, 1981; Tronson and Ross, 2004). The lecture theatre was set up as the chloroplast with grana and Photosystem I and

Appendix 1

Your task today is to make a model chloroplast.

Unless you know how the following parts fit together in a chloroplast, it is very difficult to move onto understanding the mechanics of the process of converting carbon dioxide to sugar and releasing oxygen.

In our model today, some of the structures in a chloroplast will be modelled using:

- thylacoid membranes – paper plates
- granum – paper plates
- inner membrane – plastic bag
- outer membrane – plastic bag
- Photosystem II – green sponge
- Photosystem I – yellow sponge
- chlorophyll – drawn on piece s of green paper.
- Electron transport chain – using string and beads
- NADP+ reductase – represented by a thumb tack
- ATP synthase push board pin representing (Fo) and cork for the F1 or head of the H+ATPase

Example of a question to be discussed with demonstrators (TAs) within the class:

Draw 2 water molecules in the oxygen-evolving complex. Remove a hydrogen and an electron until the only molecule remaining is O_2 (you have been given a start below). Where does the oxygen released in photosynthesis come from?

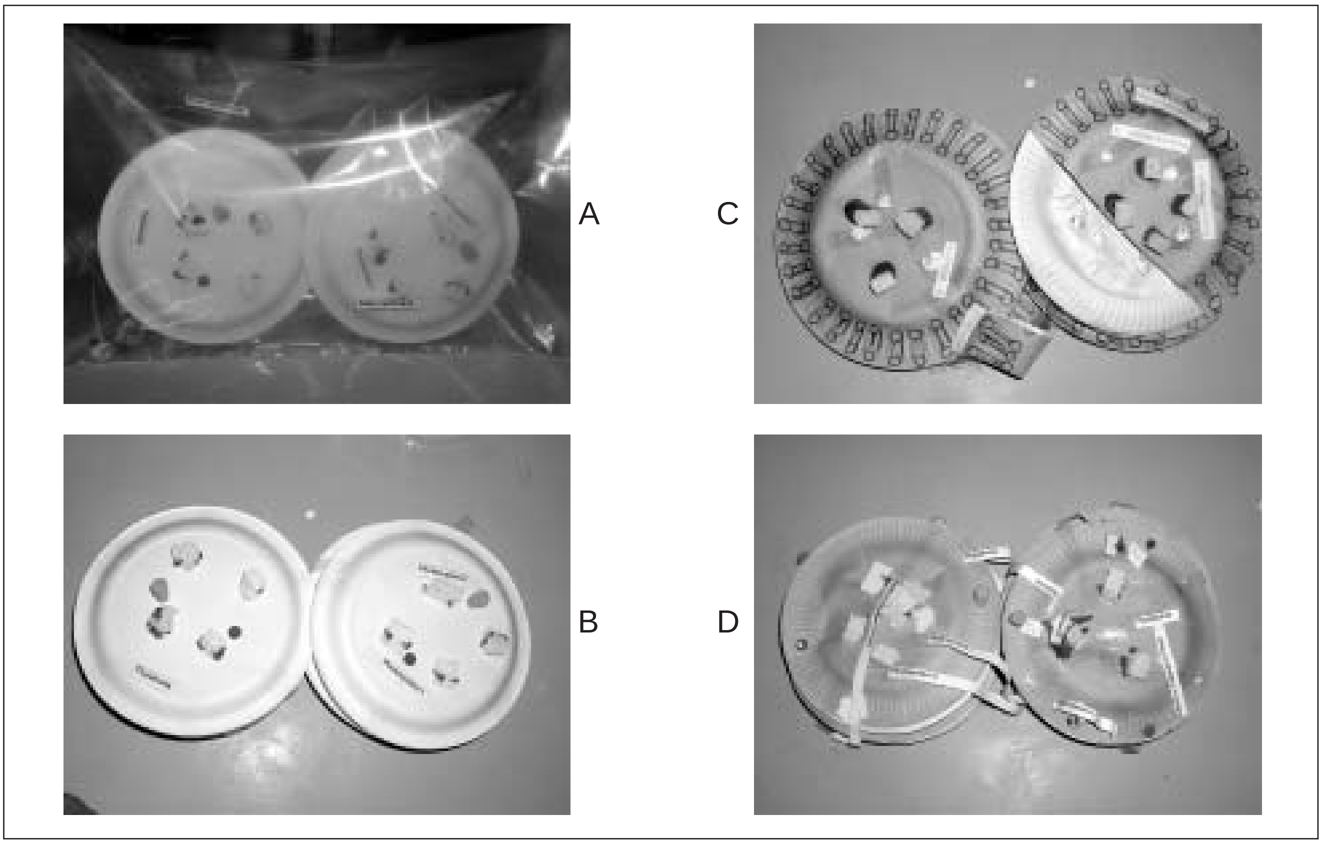


Figure 2. Differing three dimensional models of chloroplasts developed by students (Step 2a). (a) Chloroplast enveloped in two clear plastic bags which represent the double membrane found in the chloroplast, (b), (c) and (d). Models of chloroplasts removed from the plastic bags. Paper plates represent the internal membranes found within chloroplast. In model (c), the plate has been cut revealing the internal structure.

Photosystem II embedded within the membrane (protein complexes within the membrane of a chloroplast). The students were labelled as various ions, electrons and molecules by A4 paper and involved in a role play. The overhead projector was used to act as photons of light.

In the darkened theatre, the photosynthesis reaction was started when the light from the projector was shone on 'Photosystem II'. A student was asked to come and eject an 'electron' from 'Photosystem II' and take it to an 'electron acceptor' which existed at the back door of the lecture theatre. Other students in the audience were asked to visualise an electron in their cupped hands and eject it, by throwing away the imaginary electron.

A second student was then asked to replace the 'missing electron' by taking an electron from 'water', which is depicted on the board as $4H^+$ ions plus four electrons plus two oxygen molecules. In this process, the lecturer shows how an H^+ ion' is released. The overhead projector was turned off and turned back on again, and the whole sequence repeated three times (representing four photons of light in total and ejecting four electrons).

At this point, it was explained that the two oxygen atoms can combine to form an O_2 molecule, and a student physically combined these and carried a symbol for O_2 out through the door, representing diffusion of the oxygen gas out of the cell. Since this was a tiered lecture theatre, the released electrons were passed from hand to hand down the 'electron transport chain', (the steps, represented by other students) to replace the 'electrons' ejected when a 'photon' (the OHP) was shone on 'Photosystem I'. This was repeated three times until the electrons were finally passed to $NADP^+$ to form NADPH + H^+ (cofactors within the biochemical pathways).

It is important throughout this sequence to use as many students in the lecture theatre as possible and finish with H^+ diffusing through ATP synthase (the final, membrane-bound enzyme in the photosystem pathways). It was possible to simulate the physical arrangement of how electrons are transported in enzyme-mediated reactions within a membrane. To consolidate the visual aspects of learning, this role-play was combined with an increasingly complex summary of events being simultaneously constructed on an overhead (or Powerpoint or white-board) as the sequence progressed. During all these sessions students were requested to make their own pictorial image of what was occurring.

Step 4. Small-group Discussion

To facilitate discussion of any misconceptions, and to revise these complex teaching strategies, students were asked to depict diagrammatically what is occurring in a chloroplast in subsequent small-group situations (in this case a tutorial session). An example of such a construction is shown in Figure 3. Tutors and demonstrators discussed students' diagrams with them to ensure that all important concepts had been included (in a simplified form compared to Figure 1). This was followed up by advising students to revise their understanding with use of the textbook and interactive CDs on photosynthesis.

Discussion

The teaching and learning sequence described in this study used analogies, model making and role plays to make the abstract ideas in photosynthesis more tangible. In an evaluation of the teaching and learning methodologies used within the unit, students' comments in an open-ended response were overwhelming positive (Ross and Tronson 2004).

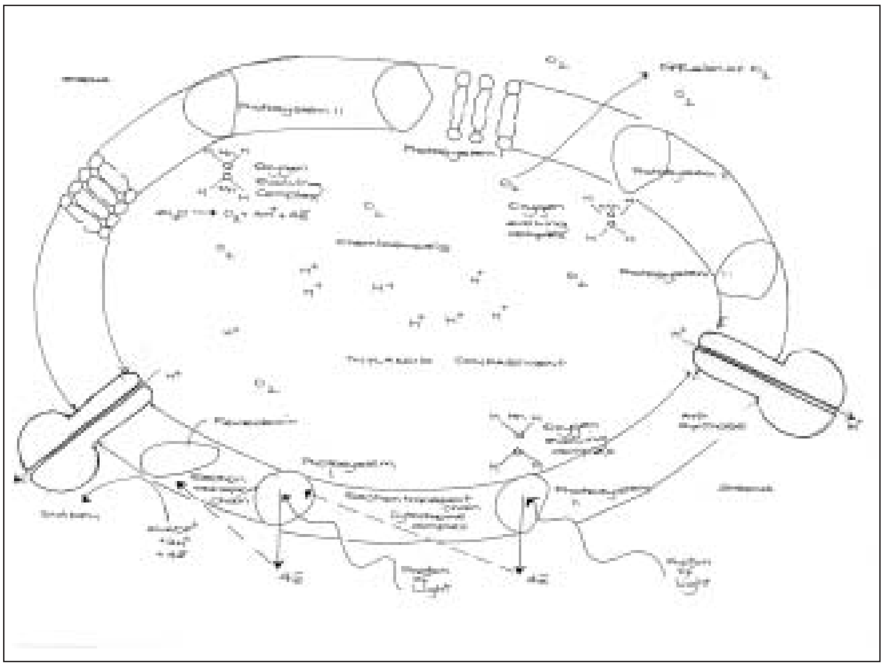


Figure 3. Typical concept drawing developed by students with assistance of demonstrators of the processes within the thylakoid membrane in the light dependent stage of photosynthesis (Step 4).

One advantage of using models is that the materials used in the model building exercises are inexpensive items. Another advantage is that student familiarity with the items used in novel ways during the practical exercise also enhances learning and recall of the scientific concepts that are represented (Oakley, 1994). If students begin to believe they can understand abstract concepts, then they are more likely to gain confidence and develop conceptual understanding of topics which are abstract and complex. This may have a positive effect on academic performance (Schommer, 1993). Essentially, the students are participating in what has been described as 'building conceptual bridges' (Glynn, 1995) through constructing physical analogies, or models, of a scientific structure or process that cannot otherwise be seen.

Modelling photosynthesis in this manner will also encourage students to have an image of the chloroplasts as three-dimensional operating systems within membrane-bound compartments. For example, once a model thylakoid envelope, made of two paper plates joined together, is damaged by actually making holes in the paper plate, photosynthesis can be 'seen' to be uncoupled. Such an understanding of the transport of electrons through membranes and compartmentalisation of hydrogen ions is not possible by completing a standard traditional practical on photosynthesis. Although this teaching and learning sequence was developed for a tertiary level education, any of these strategies could be implemented into a secondary school context.

Traditional teaching and learning strategies, which have been developed to increase conceptual understanding of photosynthesis, often emphasise macroscopic observations in an attempt to make the submicroscopic (molecular) scale understandable. Although the literature on student understanding of photosynthesis has received growing attention (Wandersee *et al*, 1994), very little of it suggests strategies to teach submicroscopic concepts. Instead, the emphasis is based on providing clarity to the notion that green plants synthesise their own carbohydrates intracellularly and do not obtain all their food from the soil (Wandersee *et al*, 1994). This indirect facilitation may not provide insight into the submicroscopic world of atoms, ions and molecules.

The need to develop effective pedagogies that help students develop a scientific understanding of these concepts in the chemical sciences has been recognised (Harrison and Treagust, 2002). We argue that a similar process needs to occur in the teaching and learning of biology. The traditional lecture, relying as it does on passive listening skills, does not help the student with learning strategies to make the connections between the macroscopic examples and the accompanying molecular/ atomic concepts. For the majority of students in today's tertiary institutions who are not metacognitive (Biggs, 2003), the submicroscopic components of photosynthesis are likely to remain a mystery. Using teaching and learning strategies which engage students will more likely result in a greater number of students using metacognitive skills to understand abstract concepts (Biggs 2003).

Some caution is necessary so that new difficulties in conceptual understanding are not created through the introduction of 'simplified' but 'incorrect' models that then become 'new' misconceptions retained by students. As educators, we need to be aware that student understanding may develop through both increments and reversals of direction rather than by a linear series of steps (Harrison and Treagust, 2002). If this is so, then this 'teach/re-teach' sequence – using a variety of teaching and learning strategies – could aid the students to increase their conceptual understanding by helping them construct a photosynthesis model for themselves, piece by piece.

Students' comments indicated that the teaching and learning strategies described in this paper increased their level of enjoyment in this difficult conceptual area (Ross and Tronson, 2004). A minority of students commented that they were somewhat embarrassed about having to act like pre-schoolers' and these individuals may have become discouraged about learning in a 'different' way. However, these students could access the more traditional routes of didactic lecture, textbook, CD-ROM, and websites for their own private study. There is evidence that individuals who successfully construct complex and elaborate conceptual structures in a given domain of knowledge tend to form positive attitudes about that domain and raise their own self-esteem (Schommer 1993; Biggs 2003). We would agree with the model proposed by Wandersee *et al*, (1994) that conceptual change may be intimately linked to affective change.

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References

Biggs J (2003) Teaching for quality learning at University – what the student does. 2nd Edition. Buckingham, UK. SRHE & OUP.

Campbell N A and Reece J B (2005) Biology. 7th Edition p193. San Francisco, USA. Pearson/Benjamin Cummings.

Driver R and Bell B (1986) Students' thinking and the learning of science: a constructivist view. The School Science Review, 67(240), 443-456.

Glynn S (1995) Conceptual bridges: Using analogies to explain scientific concepts. The Science Teacher, December, 25-27.

Gunstone R F (1995) Constructivist learning and teaching of science. Ch 1 in Teaching and learning in science: The constructivist classroom, eds. Hand B. and Prain V pp3-20. Australia. Harcourt Brace & Co.

Harrison A G and Treagust D F (2002) The Particulate Nature of Matter: Challenges in Understanding the Submicroscopic World. In: Chemical Education: Towards Research-based Practice, eds. Gilbert J K, De Jong O, Justi R, Treagust D F and Van Driel J.H. pp. 189-212. The Netherlands: Kluwer Academic Publishers.

Hodson D (1998) Teaching and learning Science: towards a personalised approach. Buckingham, Philadelphia. Open University Press.

Novak J D (1990) Concept mapping: a useful tool for science education. Journal of Research in Science Teaching, 27(10), 937-949.

Oakley C R (1994) Using socks and chromosomes to illustrate nuclear division. The American Biology Teacher, 56(4), 238-239.

Ross P M and Tronson D (2004) Towards conceptual understanding: bringing research findings into the lecture theatre in tertiary science teaching. Proceedings of Scholarly Inquiry into Science Teaching and Learning Symposium, pp. 52-57. Sydney, Australia. UNISERVE Science

Schommer Z M (1993) Comparison of beliefs about the nature of knowledge and learning among postsecondary students. Research in Higher Education, 34(3), 355-370.

Stavy R, Eisen Y and Yaakobi D (1987) How students aged 13-15 understand photosynthesis. International Journal of Science Education, 9(1): 105-115.

Wandersee J H, Mintzes J J and Novak J D (1994) Research on Alternative Conceptions in Science. In: Handbook of Research on Science Teaching and Learning, ed. Gabel G L pp. 177-210. A Project of the National Science Teachers Association. New York. Macmillan Publishing Company.

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Second IMPRESSE conference: Pupils' experimental activities

Lyn Haynes

The second gathering of IMPRESSE (Improving Education in Secondary Science in Europe) STA (Science Teacher Association) representatives, at Rennes on 22 October 2005, was organised by UdPPC, the French STA for Chemistry and Physics teachers. At the inaugural conference in The Netherlands in April 2005, IMPRESSE comprised representatives from five Europeans STAs; at Rennes there were delegates from nine. This significant increase suggests that providing a platform for science teachers to share ideas as well as examples of excellent practise is the way forward.

Why was this event such a success? Firstly, the organisation was excellent and UdPPC deserve high praise. Then, the programme: France has an active practical science programme which is why they elected to host this conference on this specific topic.

The first keynote speakers, Brenda Keogh and Stuart Naylor from the UK, addressed the audience on *Learning though experimenting*, outlining a few of their many approaches to engage pupils in thinking about science. Prior to the conference STAs were asked to submit ideas about experimental activities: one example was *At what age should experimental work start?* This query was clearly dealt with when Brenda and Stuart explained what work they undertake with pre-schoolers.

Helene Richoux, a teacher from France, who has been involved in research into '*Students' activities during Labwork in* (secondary) *Physics and Chemistry*' provided a resumé of their system. A French science inspector, Mari-Blanche Manhourat, explained the '*Assessment of experimental activities in France*' which provided valuable information about one system, especially as many countries had raised this issue of the evaluation of practical work.

These keynote themes, along with the issues raised by the STAs, provided the basis for the two afternoon workshops: *What are the objectives of the experimental activities?* and *How can experimental activities be assessed?*

Another interesting aspect of the programme were the short contributions from each STA about practical science in their country. The ASE representative, Lynne Horton, explained about Science 1 and its implementation in the primary classes thereby emphasising the value of formal primary science in the transition to secondary school. At the other extreme, it emerged that some countries do not have laboratory technicians.

Some emergent commonalities across the nations included the need for a level of active learning enabling a pupil to take ownership of the work, while developing in pupils the ability to evaluate scientific developments and socio-scientific issues with objective criticality. The platform offered by IMPRESSE to science teachers in Europe can provide opportunities for sharing and encouragement, chances to find ways round common difficulties (such as how to innovate teachers dealing with closely prescribed mandatory tasks), how to implement effective assessment and how to address the needs of the pupil-as-future-citizen in science.

Delegates at this second IMPRESSE conference voted unanimously to hold future meetings. MNU (Germany) has offered to host a conference in April 2007 in Berlin while 2008 could be ASE's turn. The concept of IMPRESSE conferences is that they run in parallel with a STA annual meeting. IMPRESSE STA delegates can then attend the rest of the host-STA's conference after the one or two day gathering, while delegates at the host-STA can choose to join in IMPRESSE sessions. At Rennes, 22 UdPPC delegates signed up to attend at least one of the five sessions of the day and many more took an interest in the IMPRESSE posters on display.

IMPRESSE is not trying to be a mover-and-shaker, but an approach to dealing with the same subject matter, client-base and purpose in numerous nations, bounded by different criteria and political yardsticks, and delivered in different tongues. Improving education in secondary science across Europe is our uniting goal. It would be wonderful to hear from more people from more STAs.

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