CBE—Life Sciences Education
Vol. 12, 287–305, Summer 2013

Article

The Effects of the SUN Project on Teacher Knowledge and Self-Efficacy Regarding Biological Energy Transfer Are Significant and Long-Lasting: Results of a Randomized Controlled Trial

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Submitted September 10, 2012; Revised February 26, 2013; Accepted March 5, 2013
Monitoring Editor: Eric Brewe

Biological energy flow has been notoriously difficult to teach. Our approach to this topic relies on abiotic and biotic examples of the energy released by moving electrons in thermodynamically spontaneous reactions. A series of analogical model-building experiences was supported with common language and representations including manipulatives. These materials were designed to help learners understand why electrons move in a hydrogen explosion and hydrogen fuel cell, so they could ultimately understand the rationale for energy transfer in the mitochondrion and the chloroplast. High school biology teachers attended a 2-wk Students Understanding eNergy (SUN) workshop during a randomized controlled trial. These treatment group teachers then took hydrogen fuel cells, manipulatives, and other materials into their regular biology classrooms. In this paper, we report significant gains in teacher knowledge and self-efficacy regarding biological energy transfer in the treatment group versus randomized controls. Significant effects on treatment group teacher knowledge and self-efficacy were found not only post–SUN workshop but even 1 yr later. Teacher knowledge was measured with both a multiple-choice exam and a drawing with a written explanation. Teacher confidence in their ability to teach biological energy transfer was measured by a modified form of the Science Teaching Efficacy Belief Instrument, In-Service A. Professional development implications regarding this topic are discussed.

DOI: 10.1187/cbe.12-09-0155
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INTRODUCTION

Biological energy flow is a foundational concept in science education. "Pathways and transformations of energy and matter" has recently been recognized as one of five "core competencies" for undergraduate biological literacy (American Association for the Advancement of Science [AAAS], 2011, p. 13). "Energy and matter: Flows, cycles, and conservation" is one of only seven cross-cutting (spanning multiple disciplines) concepts in the new K–12 framework from the National Research Council (NRC) (2012). In the recent revision of the Advanced Placement (AP) Biology Curriculum, "energy use" is cited within the third big idea, "Biological systems and their properties, including energy use, molecular components, growth, reproduction, and homeostasis" (College Board, 2012, p. iii).

As the pioneering microbiologist A. J. Kluyver wrote, "The most fundamental character of the living state is the occurrence in parts of the cell of a continuous and directed movement of electrons" (Kluyver and Van Niel, 1956, p. 71).

Understanding what gets electrons moving, the paths they follow, and the work done *as they move* are essential to understanding biological energy transfer. These fundamental, abstract ideas are precisely why energy transfer in biology has been notoriously difficult for teachers to teach and students to learn. The difficulties are obvious. First, in order to grasp this description, learners must understand core concepts regarding atomic and molecular structure, the relative tendencies of substances to attract electrons (as the standard electrode potential measured as volts), and the energy released and available for capture when electrons move. All of this is required in order to give meaning to directional net electron movement in cellular respiration and photosynthesis and the resulting energy transfer. In addition, learners must understand the sequential steps by which these cellular processes occur and place them within the structural constraints of proteins and electron carriers located on a membrane enclosed by another membrane. Finally, because the "submicro" scale at which these processes occur often interferes with the ability to visualize these events (as discussed by Gilbert and Treagust, 2009, p.6), scaffolding is necessary for students to "see" how protons are concentrated (the result of the work powered by moving electrons) and how that concentration difference can drive the coupled process of ATP production. Not only is biological energy transfer intrinsically difficult for students, it is one that challenges teachers (Anderson *et al.*, 1990; Driver *et al.*, 1994; Barak *et al.*, 1997, 1999; Wilson *et al.*, 2006; Brown and Schwartz, 2009; Parker *et al.*, 2012).

The Need for a New Approach

Misconceptions about photosynthesis and cellular respiration have been documented for more than 20 yr (Anderson *et al.*, 1990; many reviewed in Driver *et al.*, 1994; Hazel and Prosser, 1994; Barak *et al.*, 1997; 1999; Brown and Schwartz, 2009; Wilson *et al.*, 2010; and Parker *et al.*, 2012). Work from Michigan State argues for a strategy that focuses on tracking matter and energy and facilitating the ability to cross scales. Anderson and Parker's approach crosses disciplines and discusses both biotic and abiotic examples of energy transfer with the use of a picture-based summative tool for tracking both matter and energy (Mohan and Anderson, 2009; Parker *et al.*, 2012). While this strategy is designed to be useful in helping learners think about climate change on the largest scale, it does not address the *mechanism* by which *energy* is conserved and transferred in organisms at the smallest scale. Our approach has the potential to allow teachers to make sense of ideas inaccessible via current pedagogy. It is designed to help teachers and their students understand how life can occur in environments without molecular oxygen. Similarly, it is designed to make accessible fuel-cell technology that mimics the energy-absorbing chemistry of photosynthetic reaction centers (Chandler, 2010) or that runs on electrons donated by microbes. Our hope is to allow conversations about organisms that clean up pollution and about the amazing diversity of photosynthetic microbes that sustain us (Allen and Martin, 2007; Blankenship, 2010). At the same time, this strategy is designed to help learners understand biology is not a special case when it comes to fundamental laws of energy transfer, a common misconception (Barak *et al.*, 1997, 1999).

The Students Understanding eNergy (SUN) Model-Building Sequence for Understanding Biological Energy Transfer

The SUN model-building sequence was developed to induce understanding of biological energy transfer based on a general model of energy transfer occasioned by moving electrons during thermodynamically favorable or "spontaneous" reactions (Figure 1). Such "spontaneously" moving electrons can do work, and this allows for energy transfer in living things during cellular respiration and photosynthesis (Figure 1, small blue box). At the same time, the analogous experiences (Figure 1) of the SUN workshop were used to reinforce fundamental laws of thermodynamics, including conservation of matter and energy and the fact that some usable energy must be converted to an unusable form with each transfer during the irreversible processes of life (Figure 1, large blue box).

The model-building sequence of analogous experiences shown in Figure 1 includes: a video of a hydrogen-plus-oxygen explosion (the source experience), a lab involving a hydrogen fuel cell (target experience 1), the process of cellular respiration enacted using physical models (target experience 2), and the process of photosynthesis enacted using physical models (target experience 3).

During the SUN workshop, the teacher participants were encouraged to structurally align and encode (Gentner, 1983; and as discussed in Gentner, 2010) the common relational elements of these experiences through the use of an across-domain language heuristic: the ultimate electron donor, the ultimate electron acceptor, and the fact that moving electrons can do work (Table 1 and Figure 1, orange bubble). The series of experiences was designed to provide within-domain evidence for the across-domain meaning of this language when applied to both abiotic (hydrogen-plus-oxygen explosion and hydrogen fuel cell) and biotic (cellular respiration and photosynthesis) mechanisms of electron transfer and energy harvesting.

Focusing attention on commonalities of base and target experiences (Gick and Holyoak, 1983; Gentner 1983, 2010; Gentner *et al.*, 1993; Duit *et al.*, 2001; Hestenes, 2006; Podolefsky and Finkelstein, 2006, 2007a,b, 2008; see especially Coll and Lajium, 2011, discussing Duit, 1991, and Brodie *et al.*, 1994) promotes analogical thinking through structural

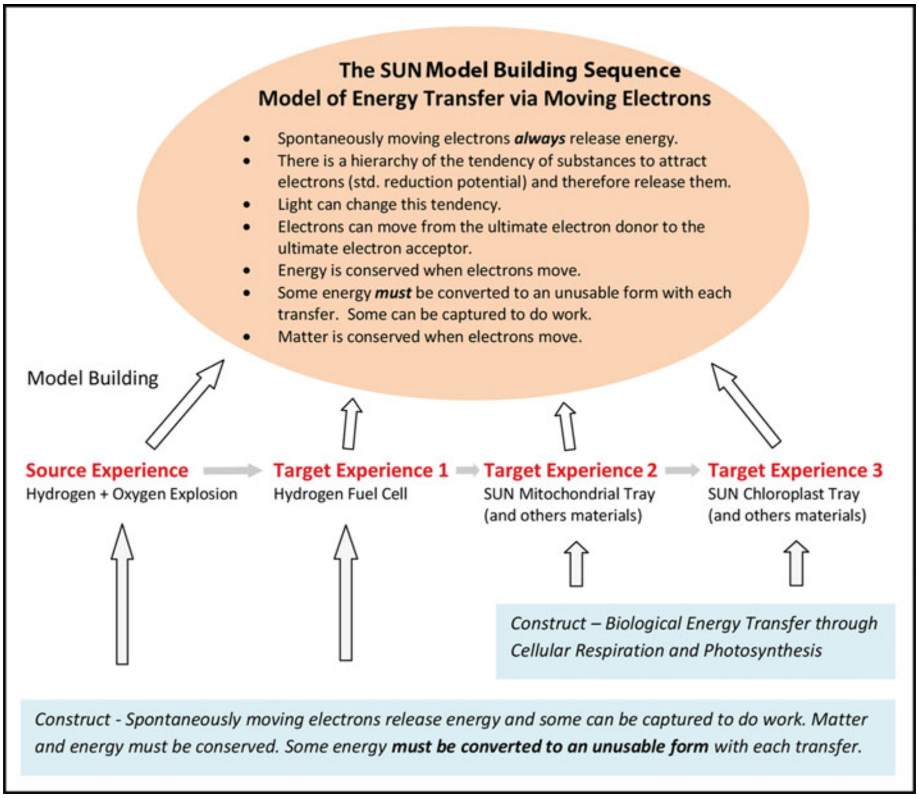


Figure 1. The SUN model-building sequence. The model of biological energy transfer is elicited through sequentially analogous experiences. From each experience, common elements are extracted to form the central common model of energy transfer when electrons move. The experiences are designed to help the learner develop an integrated model of the underlying reality of energy released by spontaneously moving electrons and the processes of biological energy transfer in cellular respiration and photosynthesis.

alignment of common elements and relationships (Gentner, 1983). Theoretically, as discussed in Gentner *et al*. (1993), structural alignment allows one to develop a common model of the similar relationships among these elements, which are not based on more apparent but possibly unrelated surface features. Gentner suggests that such comparisons promote learning through a variety of means, including abstraction, rerepresentation through uniform relational coding, inference-projection, and difference detection (Gentner, 2010, and references therein).

However, because both the base and the target experiences may be viewed differently by teacher and learner (Duit *et al*., 2001, and references therein), it is important to guide attention to relationships between elements common to each. Tutorials that "blend" a cross-domain abstract representation with a series of concrete (i.e., within-domain) representations, have been shown to promote more productive reasoning than either abstract or concrete representations alone (Podolefsky and Finkelstein, 2007a,b). Analysis of discourse and assessment choices suggests that representational pairing can drive development of discriminating personal schemata (knowledge structures) that more closely conform to canonical norms of the scientific community (Podolefsky and Finkelstein, 2007b, 2008). Indeed, Podolefsky and Finkelstein (2008) propose "the explicit linking of ideas to representations in a layered manner" (p. 2) as a way to build those salient associations.

Each of the analogous experiences during the SUN workshop (Figure 1) was discussed in terms of the common language described above (Table 1). That language heuristic was initially introduced in conjunction with a chart based on the standard reduction potentials of some biotic and abiotic

Table 1. Common language used to map from source to sequential targets[a]

Common language	Source Hydrogen + oxygen explosion	Target 1 Hydrogen fuel cell	Target 2 Cellular respiration	Target 3 Photosynthesis
Ultimate electron donor	Hydrogen	Hydrogen	Carbon compound (or other electron donor for some microbes)	Water (or other electron donor for some microbes)
Ultimate electron acceptor	Oxygen	Oxygen	Oxygen (or other electron acceptor for some microbes)	CO_2 (or other electron acceptor for some microbes)
Initial work done by moving electrons	No usable energy capture	Turning motor	Causing pumps to pump protons	Causing pumps to pump protons

[a]The ultimate electron donor, ultimate electron acceptor, and the work done by moving electrons provide common language to evoke a common model for analyzing these biotic and abiotic experiences of energy transfer.

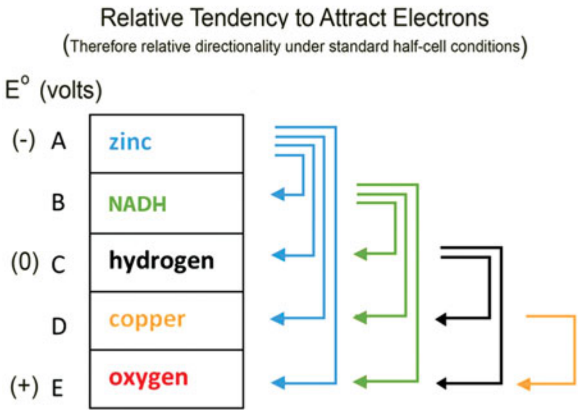


Figure 2. E^0 (ABC) chart. The predicted directionality of electron movement under standard conditions. This image is based on the relative tendencies of substances to attract electrons, i.e. standard reduction potentials (E^0) in volts relative to a standard hydrogen electrode: (Zn/Zn^{+2} [−0.76], $NADH/NAD^+$ [−0.105], H_2/H^+ [0.000], Cu/Cu^{2+} [+0.337], H_2O/O_2 [+1.229]; Fasman, 1976; Ebbing and Gammon, 2010). Note that in the figure we have substituted the known E^0 value for $NADH/NAD^+$. During the workshop, the ABC chart was regularly used without the label E^0, and sugar was substituted for $NADH/NAD^+$.

electron carriers (Figure 2). This chart indicates the relative tendency of substances to attract electrons under standard half-cell conditions. Therefore it also describes the allowable directionality of electron movement given an ultimate electron donor and ultimate acceptor. After this chart was introduced, and although we were not aware of the research on blended representations described above, ABC cards meant to evoke its meaning were blended into representations of the subsequent experiences as described below.

The underlying principle taught through this series of analogous experiences was that when electrons move between two electron carriers that differ in electron affinity as measured by their standard reduction potentials (E^0), there is a predictable standard free-energy change (ΔG^o) that makes energy available to do work. As shown in Figure 2, this principle applies whether the work is abiotic or biological. The electrons do not discriminate. Although standard conditions typically do not apply in either biological or abiotic instances of such electron movement, this standard condition can be used as a common point of reference. This idea is based on the relationship: $\Delta G^0 = -nF\Delta E^0$, where n is the number of electrons transferred, F is the Faraday constant, and ΔE^0 is the difference in standard reduction potential ($E^0_{acceptor} - E^0_{donor}$) of the donor and acceptor. During the SUN workshop, we did not dwell on the mathematical relationships; rather, teachers were taught that the amount of free energy available to do work and the direction of electron flow under standard conditions could be predicted from the electron affinity of the ultimate electron donor and acceptor (Figures 1, orange bubble, and 2).

The idea that energy is released by electrons moving in thermodynamically spontaneous reactions was first introduced through a video of a hydrogen-plus-oxygen explosion (Figure 1, source experience). Then, a "progress of reaction" chart showing the change in G^0 value of reactants and products for this reaction was introduced, after which teachers used manipulatives to see that matter was conserved (Figure 1, orange bubble). Teachers were also reminded that with each energy transfer that is thermodynamically spontaneous, energy lost to an unusable form increases the random motion and/or the random arrangement of matter (Figure 1, large blue box). (Energy transfer under reversible conditions was not considered.)

Figure 2 was central to this intervention. It was repeatedly evoked during the workshop under nonstandard conditions when discussing the rationale for the directionality of electron movement, whether in a hydrogen fuel cell (target experience 1), in cellular respiration or in a microbial fuel cell (target experience 2 and its extension), or in photosynthesis (target experience 3). For example, teachers positioned ABC cards within the physical mitochondrion and chloroplast models discussed below to indicate electron affinity at that position during cellular respiration (target experience 2) and photosynthesis (target experience 3). Because light so changes the affinity of the central chlorophyll pair (P680Chl or P700Chl) in each photosystem involved in oxygenic photosynthesis (Figure 1, orange bubble), an electron will move to an adjacent carrier. Therefore, ABC cards were used in the context of the chloroplast manipulatives (target experience 3) to explain the photosynthetic *z*-scheme (Figure 3, left).

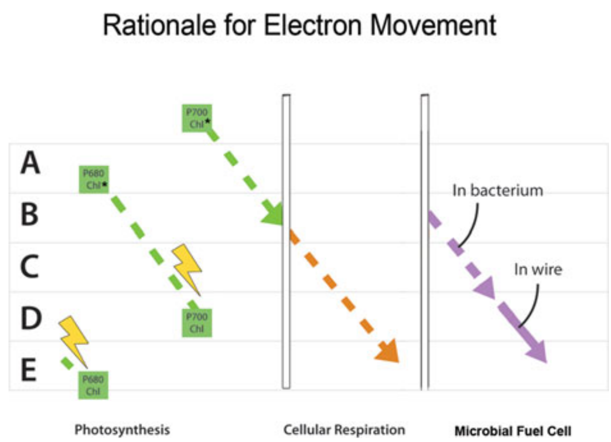


Figure 3. The rationale for electron movement in photosynthesis (PS), cellular respiration (CR), and a microbial fuel cell. Once teachers understand the meaning of the ABC chart under standard conditions, it can be used roughly (not under standard conditions) to illustrate why electrons move in both PS and CR. Light changes the tendency of the central chlorophyll pair in both PSII (P680) and PSI (P700) to attract electrons to such a great extent that electrons literally pop out and start moving (dotted line) along the path defined by constrained electron carriers. (One needs to guard against the misconception that the same electron moves from carrier to carrier.) Once electrons are handed off to fix carbon (green arrow), the carbon compound becomes the ultimate electron donor in cellular respiration. By the time electrons reach oxygen in aerobic CR and are captured with some protons to make water, they are at the level of stability of the ultimate electron donor for oxygenic photosynthesis. While electron movement in CR is driven by the relative attraction of a series of carriers, electron movement in the SUN microbial fuel cell occurs both within the microbe via such carriers (dotted line) and then along a wire (solid line) after the electrons from microbes are deposited on an electrode buried in mud. Electrons ultimately are picked up by dissolved molecular oxygen from the other electrode suspended in water. When protons are added, water is made. $4e^- + 4H^+ + O_2 \rightarrow 2H_2O$.

Teachers also constructed figures to indicate reduction potential (ABC)-driven electron movement in both cellular respiration and photosynthesis, again reinforcing target experiences 2 and 3. Notably, this activity asked teachers to blend the representation of the abstract rule shown in Figure 2 with the paths of electron movement in photosynthesis and cellular respiration to generate the first two sections of Figure 3.

Figure 3, which was developed for this paper as both a composite and refinement of figures used during this study, shows electron movement driven by ABC-based standard reduction potentials. This figure is meant to convey the physics-based rationale for electron movement during biological energy transfer and in microbial fuel cells. Figure 3 highlights the fact that the electron affinity of only the central chlorophyll pair (not the entire photosystem) is altered by light. It shows that the end point reduction potential for the ultimate electron acceptor in photosynthesis defines the electron affinity of the ultimate electron donor in cellular respiration. Its third section shows that microbes buried in the mud of a microbial fuel cell (given to all participants and developed by Milwaukee School of Engineering (MSOE) undergraduate Heather Bobrowitz based on a design by Kelvin Gregory) donate electrons to a similarly buried electrode at a more negative potential than that of oxygen. Therefore, the third section of Figure 3 reinforces the idea that microbes can use an alternative electron acceptor. It also shows that electrons move in a wire across the remaining voltage drop to oxygen in this "biotic-plus-abiotic" example of the energy made available by moving electrons.

In addition, a group activity using ABC cards reinforced the idea that a continuous source of ultimate electron donors and acceptors is required to sustain electron movement and biological energy transfer. For many organisms, including humans, those sources of course are food and oxygen, without which they die; but in this context, one can also discuss alternative electron donors and acceptors used by some microbes or possibly as yet undiscovered life-forms on other planets.

A second theoretical basis for our work is analogical bootstrapping (an increase in understanding of two previously unfamiliar processes by their one-to-one explicit comparison [Kurtz *et al*., 2001]). Teachers made explicit comparisons among the model-building experiences shown in Figure 1: for example, regarding the initial work done by electron flow in a hydrogen fuel cell (target experience 1) and that done by electron hopping in the mitochondria (target experience 2) and chloroplasts (target experience 3) of living things (See Figure 1 and Table 1).

A third basis is the use of manipulatives designed to serve as "metaphor-enhanced learning objects" that instantiate objects and their relationships within the mitochondrion and chloroplast (Table 2; Reese, 2010, p. 147, and references therein). According to Reese, "Metaphor-enhanced learning objects are scaffolding that makes *thinking* concrete" (2010, p. 146). In our experience, well-designed manipulatives provide prior-knowledge scaffolds for discussion, prediction testing, problem solving, and formative assessment. Reese suggests they provide the scaffolding that allows for "the development of deep hierarchical, highly organized, domain-specific declarative knowledge" (2010, p. 146, and references therein). If well designed, they can implicitly convey information through their surface features (see Zhang and Patel, 2006, p. 335, for a list of affordances of all types of external representations). Memory retrieval is normally based on surface features (Gentner and Landers, 1985). However, a variety of researchers have shown that deeper relationships can be retrieved when surface features are associated with matched analogues within multiply interconnected analogical relationships (as discussed in Gentner *et al*., 1993, based on her own work and that by Ross, 1989; Novick, 1988; and Keane, 1988; also see discussion in Reeves and Weisberg, 1994). Understandably, experts are better than novices at rejecting initial retrievals from memory based on mismatched surface features. Nonetheless, there is controversy regarding the usefulness of surface feature cues. Concreteness has been known to interfere with abstraction, especially for young children (Gentner and Toupin, 1986) and "poor performers" who do not grasp the underlying analogy (Goldstone and Sakamoto, 2003). On the other hand, abstract representations in the absence of blended or concrete representations decreased productive reasoning for both skilled and unskilled college students in introductory physics classes (Podolefsky and Finkelstein, 2007b).

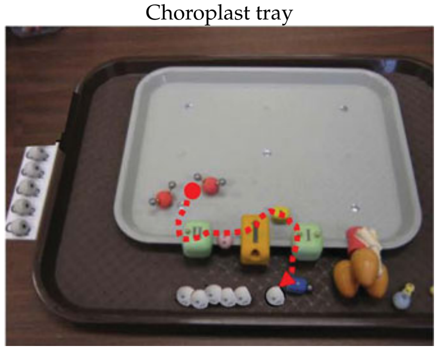
The SUN Tools: Using Common Surface Features to Highlight "Deep Features"

While the SUN workshop analogous experiences emphasized the rationale for electron movement (Figures 1 and 2), the manipulatives, animations, and other curricular materials were designed to induce rich schemata regarding the mechanisms by which moving electrons power living things. As discussed above, common surface features can sometimes focus the learner's attention on deep features and promote remembering of relational features normally difficult to retrieve from memory (Gentner *et al*., 1993). This principle was used in a variety of ways as described below.

In animations created by the authors to describe electron movement in a hydrogen fuel cell and in cellular respiration (Figure 1, target experiences 1 and 2), similar visuals and spatial relationships highlighted common elements and their relationships as the teacher toggled from one animation to the other. In each animation, the electron donor entered from the left and the electron acceptor entered from the right. Hydrogen was initially split into an electron and a proton, each of which took separate paths after that charge separation. In each process, water was formed when oxygen finally accepted electrons and attached protons. Text describing the work done by moving electrons (turning the motor attached to the fuel cell and causing pumps to pump protons in cellular respiration) appeared in the same location (target experiences 1 and 2).

Animations that described ATP synthesis included the same surface features as a mechanical model of the ATP synthase (Figures 4 and 5). Before applying the electron movement analogy to the process of cellular respiration, it was necessary for the teachers to understand how an intermediate step in cellular respiration (concentrated protons) can cause the production of ATP. They manipulated a mechanical model of the ATP synthase (Figure 4) and viewed animations of its operation (Figure 5). Both the physical model and animations were designed to show how protons fuel the

Table 2. Common objects and relationships within the mitochondrion and chloroplast tray[a]

Mitochondrion tray	Choroplast tray
	
Membrane-bound compartment (gray tray) within another membrane-bound compartment (brown tray). The brown tray defines the outer membrane, and the gray is the inner membrane. The space enclosed by the gray tray is the matrix, and the space between the trays is the intermembrane space.	Same principle, but reversed orientation. The brown tray defines the inner membrane, and the gray tray defines the thylakoid membrane. The space enclosed by the gray tray is the thylakoid lumen, and the space between the trays is the stroma.
Electrons (movable magnets). The magnetic "electrons" are moved from the ultimate electron donor to the ultimate electron acceptor via the electron transport chain.	Same principle. Electrons are moved from water to CO_2, which is attached to a 5-carbon compound in the stroma (brown space) to indicate carbon fixation.
Protons (ball-bearings). Protons are "pumped" into the intermembrane (brown) space when electrons move.	Same principle, but reversed orientation. Protons are pumped into the lumen (gray space) when electrons move.
ATP synthase. The rotor end is oriented toward the source of concentrated protons. ADP and P_i are combined to indicate production of ATP in the gray tray.	Same principle, but reversed orientation.
Proton pumps. Moving electrons cause pumps to pump protons. Magnetic "electrons" are attached to the pump and ball-bearing "protons" are pushed through to the intermembrane (brown) space.	Same principle, but reversed orientation. Protons are pumped into the thylakoid (gray) lumen when powered by the movement of electrons across the pump.
Molecular oxygen. Magnetic "electrons" and ball-bearing "protons" are added to the O_2 model to make water molecules. $O_2 + 4H^+ + 4e^- \rightarrow 2\,H_2O$.	Same principle, but reversed equation. Electrons and protons are removed from two water molecules to generate O_2. $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$
Carbons. The gray magnetic "carbons" represent carbon atoms (other atoms are not shown). They can be linked together or pulled apart to follow the flow of carbon from fixed carbon back to the air.	Same principle. One can use the magnetic carbons to represent the flow of carbon in the chloroplast from CO_2 in the air to fixed carbon.
Electron carriers such as quinone, NAD^+, and FAD. Electrons and protons can be attached to show how these carriers pick up and release electrons and are converted into QH_2, NADH, and $FADH_2$.	Same principle for picking up and releasing electrons. Here the carriers are a quinone and $NADP^+$.
Mobile carrier such as cytochrome *c*. Cytochrome *c* in the intermembrane space can ferry electrons from the middle pump (complex III) to the end pump (complex IV).	Same principle. Plastocyanin in the thylakoid lumen can ferry electrons from the proton pump to PSI.
	Green pieces represent photosystems (PSII and PSI). Electrons can be moved in response to "light."
	The flashlight represents light. Light causes electrons to pop out of the central chlorophyll pairs of PSII and PSI. One then moves them along the path to fixed CO_2. PSII electrons are replaced by electrons from water, evolving O_2.

[a]Physical models allow for transfer of meaning from one environment to the other. The dotted red line describes the path of electrons from ultimate electron donor (round end) to ultimate electron acceptor (arrow).

turning of its rotor and attached shaft. When turning, the central shaft systematically altered the configuration of attached subunits (similarly colored) that allowed binding of ADP and P_i (either virtually or as a physical model similarly colored). Each demonstrated production and eventual release of ATP (either virtually in the animation or when the ADP and P_i models snapped together inside the mechanical model). Therefore, these experiences provided blended representations of the mechanism of the ATP synthase.

Again, similar surface features were designed to draw attention to deeper commonalities within the mitochondrion and chloroplast. Physical manipulatives were designed with common features to highlight common functions and structural relationships in cellular respiration and photosynthesis during target experiences 2 and 3 (Figure 1). Table 2 shows the nested cafeteria trays (a brown tray with a smaller gray tray bolted to its surface) that highlight the crucial compartment-within-a-compartment structure of the mitochondrion and chloroplast. When used to represent the mitochondrion

Figure 4. The ATP synthase. Ball-bearing "protons" are fed into the mechanical ATP synthase, and the rotor is turned to demonstrate how protons cause the central shaft to turn and deflect the α/β subunits. Schematic models of adenosine diphosphate (ADP) and P_i (Pi) can be added to the open α/β subunit to demonstrate how concentrated protons fuel production of ATP. The inset shows a close-up of the mechanical ATP synthase model. Clear plastic covers the rotor, so users can see the ball-bearing "protons" until they exit through a small channel after one turn.

during target experience 2, the smaller gray tray represents the matrix bounded by the inner membrane; as a chloroplast during target experience 3, the gray tray represents the thylakoid lumen bounded by the thylakoid membrane. Components whose surface features and functions were introduced when the teachers learned about cellular respiration were used to indicate the same functionality in photosynthesis. For example the orange block (with pins to attach magnetic "electrons" and a hole that allows passage of ball-bearing "protons") is a proton pump activated by electron movement. Learners moved magnetic "electrons" across it and passed "protons" through it from one compartment to the other. The function is the same in the mitochondrion and chloroplast. Such careful alignment of the commonalities of these processes also makes "alignable differences" such as the relative orientation of the ATP synthase in cellular respiration and photosynthesis stand out by contrast (as discussed in Gentner, 2010). Once learners understood the consequences of electron movement in cellular respiration through target experience 2, it was necessary to introduce the meaning of only a few additional components (photosystems and the effect of light on changing the tendency of electrons to move within them) to make the consequences of electron movement in the chloroplast accessible (target experience 3).

In addition to their common surface features, the tray manipulatives (Table 2) both constrain and embody their nontrivial properties as external analogical representations. For example, the small pink "quinone" can move within the "membrane" and transfer electrons to an adjacent complex whether in the chloroplast or the mitochondrion. Such nontrivial properties serve as memory aides; provide information with little required effort, thereby relieving cognitive load; support thinking and inferences; and support "perceptual rehearsal to make invisible and transient information visible"(Zhang and Patel, 2006, p. 335). The components can be used to show the effects of electron movement on energy transfer and on the conversion of reactants (the ultimate electron donor and acceptor) into the products made after electrons move. In addition to being used with the nested-tray "organelle" environments essential for target experiences 2 and 3 in Figure 1, the tray components can also be manipulated in the context of laminated "cell mats" that allow learners to trace the flow of carbon and the flow of energy into and out of cells. This exercise reinforces the energy construct shown in the small blue box in Figure 1.

During and after the workshop, teachers were able to autonomously access information about the meaning of the tray components digitally in the interactive SUN Mitochondrial e-book (Figure 5), which can be accessed via a link at http://msoe.edu/academics/research_centers/sun. This resource maps a painting of the molecular environment of a cross-section of the mitochondrion (by D.G., who provides the Molecule of the Month feature at the Protein Data Bank) to the SUN trays and schematics (Goodsell, 2010a,b). It also provides Flash animations next to interactive jmols that allow one to explore the functions of the key protein complexes of the mitochondrion in depth, activities meant to revisit target experience 2. Therefore, this e-book provides blended representations of electron transport in the mitochondrion.

During the workshop, teachers also worked with physical and laminated models of electron carriers in the context of laminated "protein complexes" so as to define the paths and consequences of electron movement in more detail. They also gave short presentations with specificity regarding how this mechanism was interrupted in mitochondrial diseases, which is related to target experience 2. In addition, D.N. presented a lecture on basic laws of thermodynamics (Figure 1, large blue box), and how ATP powers life and energy transfer during coupled reactions (Figure 1, small blue box). An emeritus professor from University of Wisconsin–Madison, Mike Patrick, presented a lecture on light energy capture in photosynthesis (Figure 1, orange bubble). All of this content provided the "levels and strands of interconnection relationships" or systematicity principle that Gentner (1983; and as discussed by Reese, 2010, p. 135) found motivated learners to use analogical reasoning. Content useful for regular biology high school teachers guided workshop and assessment development. Table 3 shows the content of the teacher multiple-choice exam mapped to the original seven themes upon which this program was based. In addition, these themes were aligned with the then-current National and Wisconsin Standards (NRC, 1996; Wisconsin Department of Public Instruction, 2009) to ensure their content validity for regular biology. This content reflects a recommendation made almost 20 yr ago by the *Benchmarks for Science Literacy* for "careful coordination between The Physical Setting and The Living Environment benchmarks about conservation of matter and energy and the nature of energy" (AAAS, 1993, p. 343).

The SUN Workshop: Designed to Increase Teacher Self-Efficacy

In addition to helping teachers better understand these biological processes and introducing them to the new SUN

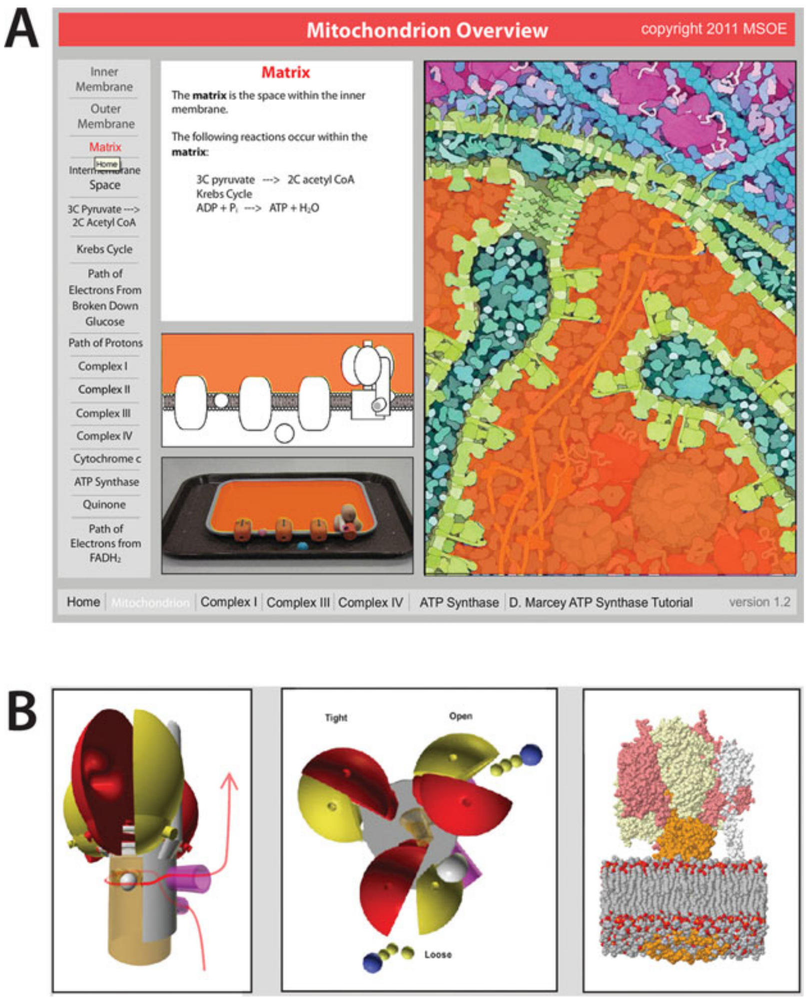


Figure 5. The SUN Mitochondrial e-book displays overview information in three contexts and allows detailed exploration of each major protein complex. (A) On the overview mitochondrion page, one can explore the meaning of the matrix and other terms in the context of a painting of its molecular architecture, in a black-and-white schematic and in terms of the SUN nested trays configured as a mitochondrion. (B) Mitochondrial protein complexes are shown in the context of a jmol-based interactive model and a Flash animated schematic. Each is also identified within the cross-mapped painting. Animated and jmol views of the ATP synthase are shown here. A SUN Chloroplast e-book is being developed as part of an NSF-funded undergraduate SUN Project.

experiences and manipulatives, the workshop was designed to build teacher confidence in their ability to successfully use these materials long after the SUN workshop. Bandura and others, as discussed in *Self-Efficacy in Changing Societies* (Bandura, 1995) decades ago, categorized four main influences regarding people's coping abilities or efficacy beliefs: mastery experiences (doing something successfully), vicarious experiences (observing successful models), social persuasion (receiving encouragement from others), and what he called "physiological and emotional states" or the effect of mood upon one's personal judgment of self-efficacy. A teacher's sense of his or her ability to teach and students' ability to learn influences a variety of effective teacher practices (as discussed in Tschannen-Moran and Hoy, 2001),

Table 3. Map of teacher 25-item multiple-choice exam to seven themes

Teacher exam questions are mapped to the content of the SUN intervention with Bloom's taxonomy levels indicated. Percentages applicable to Bloom's level and the seven topics are given.[a]	Knowledge	Comprehension	Application	Analysis/ synthesis/ evaluation	Percent
1. Fundamental laws of matter and energy	4%		4%		8
2. CR	10%	8%		12%	30
3. PS	10%	12%			22
4. Comparison of CR and PS		16%	4%		20
5. Comparison of CR to a hydrogen fuel cell		4%			4
6. Applications to other aspects of biology			12%		12
7. How ATP powers life		4%			4
Totals by Bloom's level[b]	24%	44%	20%	12%	100

[a]CR, cellular respiration; PS, photosynthesis.
[b]According to criteria in Crowe *et al.*, 2008.

including continuing to implement innovations after federal funding has expired (Berman *et al*., 1977). Although Bandura felt that mastery experiences had the greatest influence on self-efficacy, Palmer (2006) found that the main source of pedagogical self-efficacy of primary teacher education *students* was cognitive pedagogical mastery (success in understanding *how* to teach science). He found that both cognitive pedagogical mastery and cognitive content mastery (understanding the science) trumped these students' limited experience of actual teaching as a source of self-efficacy. However, Palmer felt his study did not provide the authentic enactive mastery experiences of experienced teachers and suggested such experiences might improve self-efficacy even more.

Therefore, besides attempting to increase teacher knowledge of these biological processes, we designed the SUN workshop to model use of the SUN materials and increase teacher confidence in using them. Most of the lessons designed for students were modeled as teachers critiqued them from the perspective of students. All teachers developed presentations using the materials to answer specific questions and kept a personal record of concepts learned. All took a performance assessment, using the materials to demonstrate their own understanding of each of the core processes and to become familiar with the materials. Teachers also revised their current curricula to incorporate the SUN materials for the coming year. They also were asked to deposit implementation information online every 2 mo, and they provided feedback regarding ways to improve use of the materials.

In this paper, we present the results of a randomized controlled trial (RCT) of the effectiveness of the SUN professional development intervention for regular high school biology teachers. Teachers were assessed for content understanding of the themes shown in Table 3 through both a multiple-choice exam and a drawing with explanation both immediately after a 2-wk workshop and 1 yr later. In addition, the Science Teaching Efficacy Belief Instrument, In-Service A (STEBI-A; Riggs and Enochs, 1990) was modified for biological energy transfer to determine teacher self-efficacy regarding these topics both after the workshop and 1 yr later. The distal effects of this work on students of these teachers will be discussed in a subsequent paper in preparation. Similarly, conceptual growth will be discussed in a later paper in preparation.

METHODS AND MATERIALS

The Randomized Controlled Trial

The effect of the SUN Project intervention was studied in a randomized controlled trial (RCT) only during the first year of this 2-yr trial. During the second year, all teachers had taken the SUN workshop and were using SUN materials in their classrooms.

Teachers of regular biology, largely from Wisconsin, were recruited more than a year in advance. Based on school size, demographic data, and teacher experience, equivalent school pairs were determined, and one member of each pair was randomly assigned (by flipping a virtual coin at www.random.org) to the SUN treatment group or to the control group. Ultimately 19 teachers from 18 different schools comprised the SUN group in the first year, and 20 teachers from 19 different schools participated as controls. Although assignment was by school, these numbers effectively resulted in a randomized, controlled trial to assess the teacher effects. In the first year, the treatment group attended the SUN workshop and then took SUN materials into their classrooms. In the second year, the control group teachers received the SUN workshop and took the materials into their classrooms. We followed both groups of teachers and a single class of their regular biology students each year. Out of 19 treatment and 18 control group teachers responding, three in each group had taught or were also teaching AP and/or a College Advanced Placement Program (CAPP) course of biology. On average, the treatment group teachers had taught for 15 yr, while the control group teachers had taught for 13 yr. Approximately 70% of each group of teachers held a master's degree; of those, 70–77% were in education, administration, or counseling.

We also conducted a pilot study with a small group of seven AP biology teachers and their students. Note that the quasiexperimental AP pilot had a repeated-measure design conducted over 2 yr without an independent AP pilot control group. Instead, the same set of AP teachers provided both the control condition in year 1 before attendance at the workshop and the treatment condition in year 2 after they had attended the SUN workshop. The AP pilot group teachers averaged 17 yr of experience. Of this group, 71% (5) held a master's degree, and again, ~70% of those were in education (one teacher indicated both molecular biology and science education majors). A difference in preparation between the AP and regular biology teachers was that three of the AP teachers were certified Master Educators, while none of the treatment or control group teachers held this license.

In addition to the workshop, the SUN intervention included semiannual regional meetings, a yearly classroom visit, and deposition of implementation data online every 2 mo. During the meetings, teachers shared experiences and evaluated materials used. They were also given additional instructional materials. While the materials given to treatment group teachers were focused on biological energy transfer, those given to the control and AP group teachers pertained to other aspects of biology. During the classroom visit, teachers set out all materials used to teach these topics, and their students evaluated the materials in both a written assessment and a focus group discussion. After this, the teacher was debriefed regarding his or her experiences teaching these topics and revisited his or her own evaluations of the materials in light of the classroom discussion. Treatment group teachers were prompted by the online survey every 2 mo to provide information about specific concepts taught and materials used. Control teachers provided information about concepts taught with open-ended responses. Human subjects were protected by the MSOE Institutional Review Board protocol 2110.

Administration Schedule and Analysis Methods. Treatment group teachers attended the SUN workshop in the summer of 2009 and took new instructional materials into their designated regular biology classrooms during the 2009–2010 school year. Teachers in the control and AP pilot groups were instructed to teach as they had in the past.

Preworkshop biological energy transfer knowledge data and self-efficacy data were obtained from all of the teachers at an initial meeting at the beginning of the 2009 SUN workshop (Table 4). Control group teachers and the AP pilot group attended the 2009 SUN workshop for only half of that first day so as to provide baseline data and learn about administration of assessments during the year. By contrast, the

Table 4. Teacher assessment schedule

	2009 workshop (August)		2010 workshop (August)	
Group	Beginning	End	Beginning	End
Treatment	X	X	X	
Control	X		X	X
AP pilot	X		X	X

treatment group teachers continued to attend the 2009 SUN workshop for a full 2 wk. The workshop allowed the treatment group both to learn about biological energy transfer and to develop some confidence in using the new materials they would take with them into their classrooms. At the end of the 2009 SUN workshop, the treatment group teachers provided post data regarding biological energy transfer knowledge and self-efficacy. Neither the control group nor the AP pilot group teachers were retested at that time.

During the ensuing year, all teachers attended semiannual meetings to discuss issues related to the study and share ideas; however, only the treatment group teachers received continuing professional development related to the study (controls received unrelated professional development). In addition, each treatment and control classroom was visited to obtain student evaluations of whatever instructional materials the teachers used. This visit provided another opportunity for teachers to discuss materials used with project staff.

When all teachers gathered 1 yr later at the beginning of the next SUN workshop in 2010, all groups took assessments. However, only the control and AP groups stayed for the rest of the 2010 SUN workshop. They were tested again at the end of the workshop (Table 4). Semiannual meetings and classroom visits were continued during the second year after all groups had attended the workshop and were using SUN materials in their classrooms.

The pre/post gains of the teachers who took the workshop were tested for significance using the paired-samples *t* test. In addition, pre scores were tested for significant differences using analysis of variance (ANOVA) among the three groups. Given the significant differences discovered between the baseline data of the AP pilot group and the other two groups, gains made by the treatment group teachers as a result of the workshop were compared with both the control and AP pilot groups. In interpreting hypothesis-testing results, the type I error level was set at 0.05, a common practice for research studies like this. In other words, in the *Results* section, any p value lower than 0.05 is considered a significant effect. In addition to the p value, effect size measured by Cohen's d (Cohen, 1988) is given wherever appropriate. A suggested yardstick to interpret d (Cohen, 1988) when comparing two different groups is: 0.2 as a small effect, 0.5 as a medium effect, and 0.8 and greater as a large effect. Note that this yardstick does not apply when comparing pre- to postworkshop gains by the same group.

Teacher Knowledge and Self-Efficacy Assessments

We used mixed quantitative and qualitative methods to assess gains in teacher understanding and attitudinal changes as a result of the SUN workshop and continuing professional development. Because of the timing of assessments (Table 4), we were able to test long-term effects of the SUN intervention 1 yr later relative to randomized controls who had not yet taken the SUN workshop. However, because the AP pilot study has a repeated-measure design in which the AP pilot group teachers served as a control group during the first year and as a treatment group after receiving the workshop, long-term effects on AP teachers were not measured.

SUN Multiple-Choice Exam with Likert-Style Confidence Scale. The 2009 teacher pre/post content exam contained 25 multiple-choice energy transfer questions. The 2010 exam contained an additional five items, which we added in order to evaluate them as future replacement items, but they were not considered in the analyses below. Along with each multiple-choice question, a confidence rating was sought on how confident the teacher felt in answering each item. The rating was on a Likert-scale from 1, not at all, to 5, extremely. Two exemplar questions are indicated below. Each provides four answer choices.

Q#3. A green plant is placed alone in a closed container that contains air. A light shines on it. What must occur during the following week?

(a) ONLY cellular respiration
(b) ONLY photosynthesis
(c) BOTH cellular respiration and photosynthesis
(d) NEITHER cellular respiration nor photosynthesis

How confident are you of your answer to question #3				
1	2	3	4	5
Not at all				Extremely

Q#12 Which is required for BOTH a hydrogen fuel cell and cellular respiration in humans?

(a) Oxygen gas
(b) Hydrogen gas
(c) Glucose or some other carbon source
(d) Carbon dioxide

How confident are you of your answer to question #12				
1	2	3	4	5
Not at all				Extremely

The multiple-choice exam was based on an earlier form developed for an Upward Bound pilot by the authors and examined by our scientist advisory board. How well this exam captured the major content areas of the SUN program was investigated by constructing a test blueprint. The test blueprint maps each of the 25 items in the exam to core concepts arranged under the seven themes around which the workshop was developed. The Bloom's taxonomy level of each question was also determined by a consensus of five key personnel, using the analysis of biology content by Crowe and colleagues as a guide (2008). (See Table 3 for a summary and Supplemental Figure S1 for the test blueprint.) Notably, 68% of the

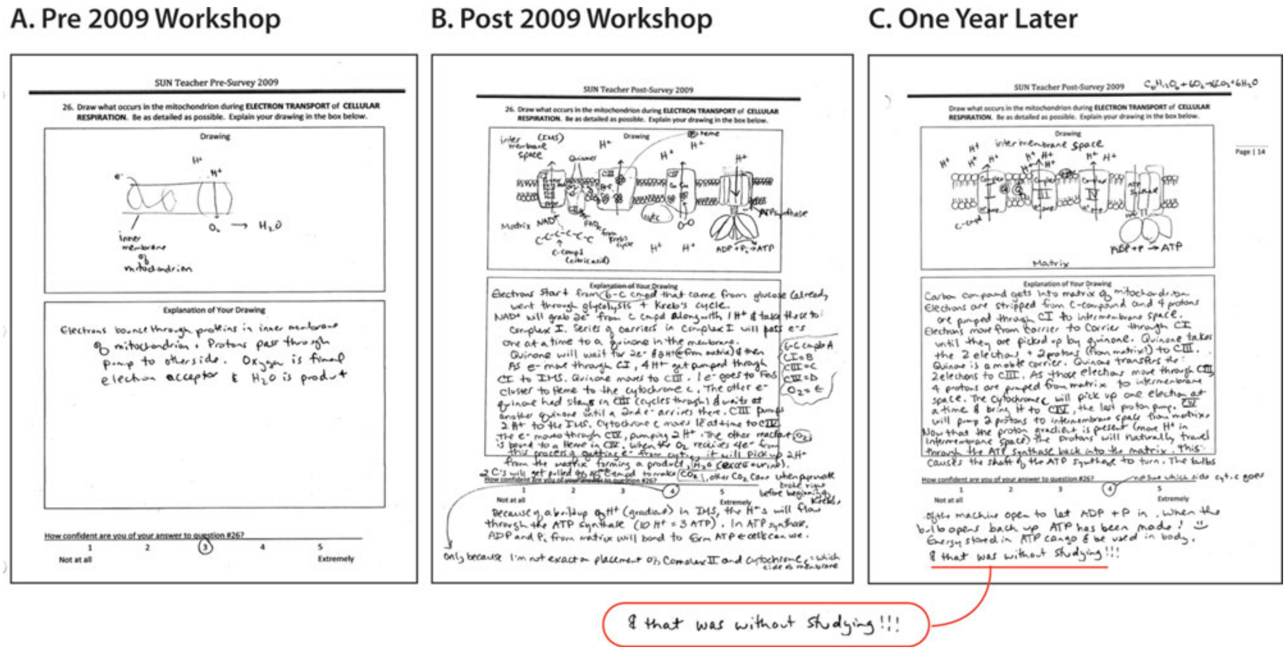


Figure 6. Example of a teacher drawing pre-2009 workshop, post-2009 workshop, and 1 yr later, at the beginning of the 2010 workshop. (Note that although the part C assessment is labeled "2009," it was administered in 2010.) Larger views are available in Figures S2–S4. The accuracy, clarity, and rich detail indicate substantial conceptual development and retention as a result of the SUN Project. This teacher's drawing with explanation score was ranked eighth out of the 19 participants just after the workshop, and fifth out of the 19 participants 1 yr later. The ease of recall 1 yr later is indicated by the comment "& that was without studying!" Conceptual retention of the core process is excellent. While some detail is missing, this is expected, given the needed focus on main ideas in a regular biology classroom.

25 items were judged to require only lower-order cognition at the level of knowledge or comprehension. Only 20% required application of knowledge, and 12% tested higher-order cognition at the level of analysis or evaluation. The great majority of the 25 items (19) addressed cellular respiration, photosynthesis, or the comparisons of these to each other or to a hydrogen fuel cell (Table 3). Only two items tapped fundamental laws of matter and energy. While we found that instruction in control classrooms largely focused on the reactants and products, five items on the teacher multiple-choice test required knowledge of the process of cellular respiration and four items required knowledge of the process of photosynthesis to answer correctly.

To further evaluate the statistical quality of these items, we conducted an item analysis based on the posttest responses. Due to the relatively small sample size ($n = 19$), item difficulty and item discrimination parameters were computed based on classical test theory, under which item difficulty is defined as the percentage of correct responses, and item discrimination is the correlation between item response and total score. While the difficulty parameter shows how many teachers answered an item correctly, the discrimination parameter actually is a better index of item quality, as it tells who had the correct answer. Overall, these items were quite easy for teachers after the workshop. Out of 25 items, 14 of them were answered correctly by almost all teachers. Even the hardest item received 13 correct responses out of 19 teachers. Item discrimination was quite high for the harder items. However, we did identify some items with unsatisfactory discrimination. We will revise this test to include items that are more difficult, and hopefully therefore more discriminatory, for future use.

SUN Drawing with Written Explanation Assessment. The drawing with written explanation assessment (Figure 6 and Supplemental Material) says, "Draw what occurs in the mitochondrion during electron transport of cellular respiration. Be as specific as possible. Explain your drawing in the box below." This assessment was developed by the project to include concepts from four broad categories: 1) general lower-level criteria regarding structures and their spatial relationships, 2) the overall process of cellular respiration, 4) the specific production of ATP, and 4) energy transformations. The authors created a 35-item rubric with $\geq$0.90 interrater reliability, based on three raters who met to clarify the rubric and gain consensus after beginning to grade and then grading independently. Sample criteria and clarifications of exemplar criteria are shown in Table 5. Notice that some criteria address the same concept but vary regarding the degree of specification. For example, criteria 18 and 19 both address the formation of water when oxygen accepts electrons in cellular respiration. However, criterion 19 requires more specific information regarding the numbers of electrons and protons used as a requirement for receiving credit.

STEBI-A Modified for Energy Transfer. Self-efficacy was measured using a form of the STEBI-A, which was originally developed to assess the science teaching self-efficacy of elementary teachers (Riggs and Enochs, 1990). We modified it to assess self-efficacy of high school teachers with regard to energy transfer. Each item is followed by five choices to indicate strongly agree (SA), agree (A), uncertain (UN), disagree (D), or strongly disagree (SD). The choices follow each item.

Table 5. Sample criteria from the 35-item rubric for teacher drawings with explanation[a]

Criterion[b]	Description	Clarification
3	ATP synthase is shown.	The key idea is that the ATP synthase is a structure that is associated with this process. The ATP synthase needs to appear in the drawing in some fashion, so that it is identifiable as the ATP synthase or something that makes ATP. If it is a squiggle or poor schematic, the text needs to clearly describe that it is present, and the poor schematic needs to be enhanced by some description of its function in the text. (This is a low-level criterion.)
18	Water is made when oxygen accepts electrons (and protons but this detail is not required for credit).	The key idea is that water is made when oxygen accepts electrons. The fact that it also must attract protons is not required for credit. A variety of formulae or just the statement will garner credit. The formula is not required for credit.
19	O_2 picks up 4 electrons and 4 protons to make two molecules of water	The key idea is that water is made when molecular oxygen accepts 4 electrons and 4 protons or it is made when O accepts 2 electrons and 2 protons. *One may indicate that O picks up 2 electrons and 2 protons to make a molecule of water. Just showing circles is not unambiguous unless it is clear these represent protons or electrons. One cannot just say that O_2 picks up 4 electrons or that O picks up 2 electrons.*

[a]The directions say: "Draw what occurs in the mitochondrion DURING ELECTRON TRANSPORT of CELLULAR RESPIRATION. Be as detailed as possible. Explain your drawing in the box below."
[b]One criterion may evaluate a concept similar to another but at a more stringent level.

The total possible score on the 25-item test is 125. Three exemplars are below:

> #1. When a student does better than usual in energy transfer, it is often because the teacher exerted a little effort.
>
> #17. I find it difficult to explain to students why energy transfer experiments work.
>
> #25. Effectiveness in energy transfer teaching has little influence on the achievement of students with low motivation.

The STEBI-A–modified survey can be divided into two subscales: the Personal Science Teaching Efficacy Belief (PSTE) subscale, regarding belief in one's ability to teach energy transfer, and the Science Teaching Outcome Expectancy (STOE) subscale, regarding one's expectation students will be able to learn about energy transfer. The reliability coefficient alphas (Cronbach's alpha) for the subscales of the original STEBI-A for elementary classrooms were respectively 0.92 and 0.77 (Riggs and Enochs, 1990), where a value greater than 0.7 is usually considered a reliable measure. Using a sample size of 42 pretests and 24 posttests, we have determined the overall coefficient alpha for the SUN-modified STEBI-A to be 0.88, based on pretest scores, and 0.79, based on posttest scores. The coefficient alpha for the PSTE subscale (consisting of 13 items and a possible total score of 65) is 0.92, based on the pretest scores, and 0.77, based on the posttest scores. However, the coefficient for the STOE subscale consisting of 12 items is only 0.64 in each case. This is a bit lower than acceptable, but it should be noted that this sample size is not large. Therefore, we will not report the STOE subscale scores. However, we will address the overall results and results regarding the PSTE subscale, both of which represent goals of our program.

RESULTS

We determined significant effects of the SUN workshop for all groups in terms of knowledge and self-efficacy, and we additionally found that the treatment group sustained significant effects even 1 yr later for each outcome.

Teacher Knowledge Effects

While the treatment and control groups were initially similar, teachers significantly increased their understanding of biological energy transfer as a result of the SUN workshop and maintained a significant increase even 1 yr later compared with their preworkshop score and compared with the preworkshop 2009 scores of randomly assigned controls. This result is evidenced both by their performance on the multiple-choice exam and by the drawing with explanation assessment.

Teacher Knowledge Indicated by a 25-Item Multiple-Choice Exam. Initially, the control and treatment groups were indistinguishable on a multiple-choice knowledge assessment (treatment mean = 17.1 and control mean = 18.1 out of 25 points; $p = 0.37$), and they scored significantly lower than the AP pilot group (21.9 mean, $p < 0.01$, $d = 1.94$). However, as determined by a paired-samples t test, participation in the SUN workshop significantly increased treatment group achievement (21.6 mean vs. 17.1 mean, $p < 0.001$, $d = 1.16$) to the level of the small comparison group of AP pilot group teachers who had not yet attended the workshop (21.6 mean treatment group 2009 postworkshop vs. 21.9 mean AP pilot group 2009 preworkshop; $p = 0.88$). Higher achievement levels by the AP pilot group teachers prior to the workshop were expected, because that group is normally responsible for teaching this content at a much more detailed level. Therefore, the treatment group teachers' content understanding improved significantly from pre-exam to postexam by 4.6 points to 21.6, which is more than one SD above the presurvey score (see Figure 7). Interestingly, the treatment group preworkshop

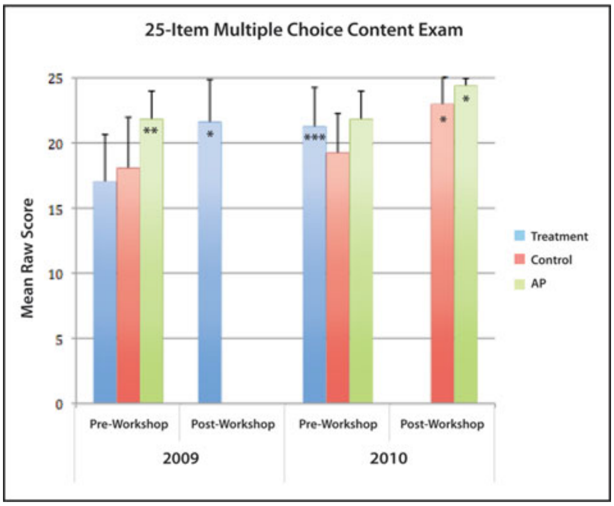


Figure 7. Results of 25-item multiple-choice exam means and SDs by group: treatment (blue), control (red), and AP pilot group (green). Preworkshop 2009 refers to the beginning of the SUN workshop at which all assembled initially so as to obtain baseline data. Postworkshop 2009 refers to the end of the 2009 SUN workshop, which only the SUN Group attended for the full 2 wk. While only the control and AP groups attended the 2010 workshop for its duration, the treatment group also provided preworkshop data on the first day. The mean score of each teacher group was significantly increased as a result of the SUN workshop. The treatment group continued to demonstrate significant gains 1 yr later. Mean scores out of a possible 25 points and SDs are given for each group. *, significant difference pre- to postworkshop for each group as a result of the workshop; **, initial significant difference between the AP group and the other groups prior to the 2009 SUN workshop; ***, a continued significant difference of the treatment group mean 1 yr later relative to the preworkshop 2009 treatment and control group and preworkshop 2010 control group means. Other comparisons are discussed in *Results*.

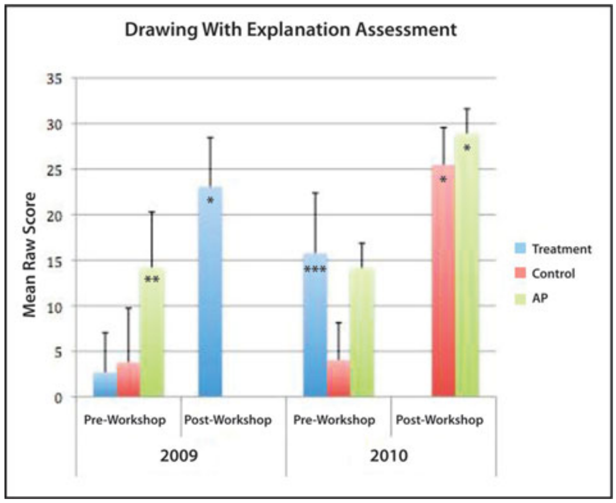


Figure 8. Results of the teacher drawing with explanation assessment means and SDs by group: treatment (blue), control (red), and AP pilot group (green). The overall drawing mean score of each teacher group was significantly increased as a result of the SUN workshop. The treatment group continued to demonstrate significant gains 1 yr later. Mean scores out of a possible 35 points and SDs are given for each group. *, significantly different mean for each group pre- to postworkshop (note that the treatment group mean score as a result of the 2009 workshop was also significantly higher than the 2009 prescore of the AP pilot group); **, the initial significant difference between the AP group and the other groups at the beginning of the 2009 SUN workshop; ***, a continued significant difference of the treatment group mean 1 yr later relative to the preworkshop 2009 treatment and control group means and the preworkshop 2010 control group mean. Other comparisons are discussed in *Results*.

and postworkshop multiple-choice exam scores are not highly correlated ($r = 0.34$, $p = 0.16$) suggesting either that initially poorly performing teachers profited more from the workshop and/or there was a ceiling effect for the initially high-achieving group. The mean scores with SDs of the treatment group (who attended the SUN workshop and afterward used the materials in their classrooms) and the control and AP pilot groups are shown in Figure 7.

In addition, the treatment group demonstrated long-term retention of knowledge gains (Figure 7). The treatment group was retested 1 yr later, along with all other participants at the beginning of the 2010 SUN workshop (Table 4). Notice that the treatment group mean score (21.3) continued to be significantly higher than their preworkshop score from 2009 (17.1, $p < 0.001$, $d = 1.31$) and versus the mean score of the control group in 2009 (18.1, $p < 0.01$, $d = 0.94$). The treatment group 2010 mean score was also significantly higher than the control group 2010 mean in the retest prior to the workshop (19.3, $p = 0.049$) The increase in the mean score of the control group from 2009 to 2010, still prior to their attending the workshop, was not significant ($p = 0.25$). Notably, there was little perceptible change in the treatment group knowledge score even after a year (21.6 postworkshop in 2009 and 21.3 in 2010, $p = 0.74$). (The *Discussion* addresses a possible effect of the differential prompts for online data deposition between treatment and control group teachers.) All groups benefited from the SUN workshop, including the AP pilot group (24.4 postworkshop vs. 21.9 preworkshop, $p < 0.02$, $d = 1.80$). One caveat in interpreting the AP pilot group results is that the sample size is small, with only seven teachers. In addition, the high mean score (24.4 out of 25 items correct) on the postexam may indicate a ceiling effect.

Teacher Knowledge Indicated by a Drawing with Explanation Assessment. As discussed before, the drawing with explanation exam was given in both 2009 and 2010 to all participants. In addition, it was given at the end of each workshop to those who attended (Table 4). Again, the control and treatment groups were initially not different in their ability to describe what occurs during cellular respiration as a result of moving electrons ($p = 0.51$). The treatment group achieved a mean of only three items correct out of 35, while the control group had a mean of four items correct. As expected, the AP pilot group scored significantly higher than either of the randomized groups initially, having a mean of 14 items correct ($p < 0.001$). However as a result of the SUN workshop, the treatment group made significant gains, achieving a mean of 23 items correct. This was a significant gain relative to the mean preworkshop scores of the randomized control group (3, 2009, $p < 0.001$, $d = 3.38$) and even relative to the AP pilot group (14, 2009, $p < 0.001$, $d = 1.58$). One can follow these results via the blue bars in Figure 8.

While the magnitude of the gain was not maintained a year later (a mean of 23 postworkshop in 2009 and of 16 in 2010), the treatment group still scored significantly higher than its

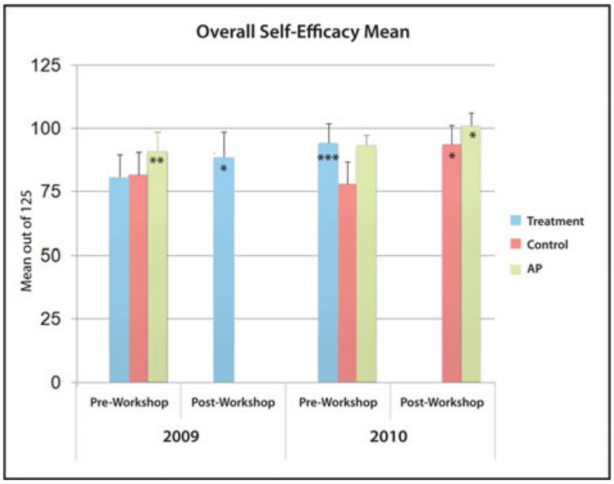


Figure 9. Results of the STEBI-A modified for biological energy transfer self-efficacy survey means and SDs by group: treatment (blue), control (red), and AP pilot group (green). The overall self-efficacy mean of each teacher group was significantly increased as a result of the SUN workshop. The treatment group continued to demonstrate significant gains 1 yr later. Mean scores out of a possible 125 points and SDs are given for each group. *, a significantly different mean for each group pre- to postworkshop; **, the significant difference between the AP group and the other groups' means at the beginning of the 2009 SUN workshop; ***, the continued significantly different treatment group mean 1 yr later relative to the 2010 control group before they attended the SUN workshop. Other comparisons are discussed in *Results*.

2009 preworkshop mean value (3, $p < 0.001$, $d = 2.34$) and higher than the mean of the control group in 2009 (4, $p < 0.001$, $d = 1.91$) and the retested control group in 2010 prior to the workshop (4, $p < 0.001$, $d = 2.01$). In all these cases, the large d indicates the huge effect size obtained from the treatment on the drawing test. Even 1 yr later, the treatment group mean was still comparable with the preworkshop mean score of the AP teachers in 2009 (Figure 8, 14, green bar, $p = 0.50$ and in 2010 (Figure 8, 14, green bar, $p = 0.48$). Notice the consistency in the mean drawing score for the AP comparison group a year later in the absence of the workshop ($p = 0.99$). In addition, the drawings themselves provide a snapshot regarding the teachers' conceptual understanding of the process of cellular respiration. They reflect clarity regarding how the movement of electrons causes proton pumping, which results in the production of ATP (Figure 6 and Supplemental Material).

Teacher Self-Efficacy Effects

Teacher Self-Efficacy Indicated by the STEBI-A Modified for Energy Transfer. Significant gains were also demonstrated by each group as a result of the workshop with regard to their overall self-efficacy score. In addition, both the treatment and control groups' personal belief that they could teach this topic (the PSTE subscale score) increased significantly as a result of the workshop. Interestingly this gain in personal belief also increased significantly for the treatment group teachers after using the SUN materials in their classrooms and experiencing the continuing professional development offered by the SUN Project intervention. (See Figure 9 for the 2-yr comparison and Table 6 for the PSTE subscale results.)

By ANOVA, prior to the first workshop and as expected, both the treatment and control groups scored significantly lower on their pre scores relative to the pre scores of the AP teachers (average total score of 81 and 82 respectively vs. 91 for the AP pilot group out of a possible total score of 125, $p < 0.05$). By the end of the 2009 workshop, the treatment group increased their overall self-efficacy significantly to a mean score of 88 ($p < 0.001$). During the following school year, only the treatment group used SUN materials in the classroom; the control and AP pilot groups conducted business as usual. Over that school year, the treatment group self-efficacy mean increased to 94. This treatment group mean increase in 2010 was not significant relative to the postworkshop mean a year earlier (88, $p = 0.07$) but this sustained increase in self-efficacy was significant relative to that of the control group before they attended the workshop in 2010 (78, $p < 0.01$). The year-later treatment group mean in 2010 was similar to the pre-2010 workshop score achieved by the AP group. The treatment group mean was 94 in 2010, while the AP pilot group mean was 93 ($p = 0.76$) before they attended the workshop that year. Notably, the treatment group mean 1 yr after the SUN workshop was also not different than the 2010 postworkshop score of 94 achieved by the control group. In addition, even the AP pilot group significantly increased their overall self-efficacy mean as a result of the SUN workshop from 93 to 101 ($p < 0.005$, Figure 9).

The treatment group PSTE subscale mean regarding their personal belief in their ability to teach these topics also improved significantly during the 2009 workshop (from 40 to 47, $p < 0.01$) and improved significantly *even more* by the 2010 preworkshop test date to 51 ($p < 0.01$) out of a possible 65 points (see Table 6 for means and SDs). Therefore, the treatment group teachers' belief in their ability to teach these energy topics increased significantly relative to controls

Table 6. Teacher self-efficacy subscale results for the STEBI-A[a] modified for biological energy transfer PSTE belief subscale

	2009 SUN Workshop attended by treatment group[b]			2010 SUN Workshop attended by control and AP pilot groups[b]		
Group	*n*	First day	End of workshop	*n*	First day	End of workshop
Treatment	19	40.21 (7.06)	47.04[c] (6.23)	19	51.37* (4.74)	Not tested
Control	20	41.06 (8.77)	Not tested	18	37.67 (7.33)	50.89[c] (6.04)
AP pilot	7	47.86 (4.98)	Not tested	7	50.29 (3.40)	54.57 (3.78)

[a]Riggs and Enochs, 1990.
[b]*n* = Number of teachers. Mean out of 65 points is given with SD in parentheses.
[c]Significant effects of the SUN workshop and intervention. These are discussed in the text.

Table 7. Teacher confidence in knowledge results regarding Likert response (1 to 5) under each item of the 25-item multiple-choice exam

	2009 SUN workshop attended by treatment group[a]			2010 SUN workshop attended by control and AP pilot groups[a]		
Group	*n*	First day	End of workshop	*n*	First day	End of workshop
Treatment	19	3.18 (0.70)	4.56[b] (0.43)	19	4.34[b] (0.48)	Not tested
Control	20	3.14 (0.71)	Not tested	18	3.19 (0.51)	4.54[b] (0.38)
AP pilot	7	4.13 (0.47)	Not tested	7	4.33 (0.42)	4.93[b] (0.05)

[a]n = Number of teachers. Mean is given with SD in parentheses.
[b]Significant effects of the SUN workshop and intervention. These are discussed in the text.

after the workshop and during the first year they used these materials in their classrooms and attended semiannual meetings. Notably, the control group also significantly increased their mean PSTE score (from 38 to 51, $p < 0.01$) as a result of the workshop, but the AP group gain from 50 to 55 out of a possible 65 ($p = 0.07$) was not significant. Perhaps this was because of the small sample size of seven teachers or because their belief in their ability to teach this topic was understandable already quite high as AP teachers before the workshop began (Table 6).

Teachers' Confidence in Their Knowledge. Teachers indicated confidence in their answers on the multiple-choice exam using a Likert scale from 1 to 5, as described earlier. The impact on teachers' confidence in their answers followed the pattern seen previously (see Table 7 for means and SDs). The treatment and control initial means in 2009 were equivalent (3.2 and 3.1, $p = 0.88$) and significantly lower than those of the small AP comparison group (4.1, $p < 0.01$). However, as a result of the workshop, all groups significantly improved their mean scores. The treatment group gain pre/postworkshop was from 3.2 to 4.6 ($p < 0.001$), the control group gain was from 3.2 to 4.5 ($p < 0.001$), and the AP group gain was from 4.3 (when retested again in 2010) to an almost perfect score of 4.9 ($p < 0.01$). Even 1 yr later, the treatment group teachers maintained a score of 4.3, which was similar to that of the AP comparison group in 2010 before they had the workshop (4.3, $p = 0.97$). This treatment group score of 4.3 also continued to be significantly higher than that of the control group as measured before the controls attended the 2010 workshop (3.2, $p < 0.01$).

DISCUSSION

The SUN Project has addressed the long-documented difficulty of learning about biological energy transfer by developing a new discourse regarding what powers life. While many efforts in the past have used the overall equations for cellular respiration and photosynthesis as the anchor for discussion, the fundamental principle taught here is that energy is released by moving electrons in thermodynamically spontaneous reactions and is available for transfer. The point is driven home by the isomorphism in language used to frame four experiences that highlight this principle (Figure 1 and Table 1). For each experience, that language describes the ultimate electron donor, the ultimate electron acceptor, and the fact that moving electrons can do work (Table 1). A simple ABC chart represents the standard reduction potentials and, therefore, the potential for electron movement between a variety of organic and inorganic substances (Figure 2). That point of reference is then used to explain electron movement and energy transfer via moving electrons during four analogous experiences *not* under standard conditions (Figure 1 and Table 1): a hydrogen-plus-oxygen explosion (source experience), a hydrogen fuel cell (target experience 1), and carefully designed manipulatives (metaphor-enhanced learning objects) that allow learners to enact, practice, discuss, compare, solve problems, predict outcomes, and analyze the mechanisms of cellular respiration (target experience 2**)** and photosynthesis (target experience 3).

Discussion of Teacher Knowledge Effects

The long-term effects of the SUN Project intervention on teacher knowledge and self-efficacy have been demonstrated in the results reported above. The effect sizes of the change in knowledge as indicated by both the multiple-choice exam mapped to the workshop themes (Table 3) and the drawing with explanation are extremely large, given that an effect size of 0.8 is considered large when comparing across groups, but does not apply to pre- to postworkshop comparisons (Cohen, 1988). Treatment group regular biology teachers demonstrated a 1.16 effect size gain on the multiple-choice exam as a result of the workshop and maintained a large 0.94 effect size gain a year later relative to the 2009 prescores of the randomly assigned controls. Even the small group of AP pilot teachers benefited from the workshop, demonstrating a 1.80 effect size gain pre- to postworkshop (Figure 7). Because of the structure of the pilot study, it was not possible to assess long-term learning by the AP teachers.

Similarly, teachers in the treatment group made very large and long-lasting gains in their ability to produce a drawing with written explanation of the process of cellular respiration in the mitochondrion. The effect size of the pre- to postworkshop gain was 3.38, as their raw scores increased from a mean of 3/35 to 23/35 criteria regarding the structures, components, mechanism, and energy transfer process during cellular respiration (Figure 8). Interestingly, the treatment group teachers scored significantly higher than the small incoming AP pilot group, with a very large 1.58 effect size difference. One year later, the treatment group retained a very large 2.34 effect size increase over their preworkshop scores, which is remarkable. At that point, their achievement level was similar to the mean of the AP pilot comparison group in the absence of the workshop. As the "high average" example shows in Figure 6 (with enlargements of each drawing in the Supplemental Material), this teacher was able to produce an enormous amount of accurate detail about this process even 1 yr later and, as she wrote, "without studying." The year-later drawings suggest that while some detail is no longer present, the treatment group teachers have retained a thorough understanding of cellular respiration. This result for regular biology teachers is not unexpected, given that their classroom instruction focuses on the essential components of the process and not on the details.

The data also indicate that the randomly assigned treatment group and control group of regular biology teachers (16–17% of each group also taught or had taught AP or CAPP biology) were initially equivalent with regard to their content knowledge, both in terms of the multiple-choice exam and the drawing with explanation assessment; and that their knowledge was initially significantly lower than that of a small AP teacher comparison group (Figures 7 and 8). It is interesting that *all* teacher groups, whether those in the regular biology cohort or those teaching AP biology, significantly improved their knowledge as a result of the workshop (Figures 7 and 8). The ceiling effect of the multiple-choice exam may be a result of the large percentage (68%) of items requiring only recall or comprehension (Table 3). In future studies, we will increase the number of items requiring higher-level thinking skills and also increase the number of items that focus on fundamental laws of energy transfer.

It is noteworthy that the prompts within the online implementation survey the treatment group received every 2 mo regarding concepts mentioned in class are quite similar to the concept categories present in the test blueprint (Figure S1). However, in the online data survey, "photosynthesis and cellular respiration" was a single category. For example, the survey prompted teachers to indicate the number of classes in which they mentioned "reactants and products of cellular respiration or photosynthesis" or "ABCs or fuel cell applied to cellular respiration or photosynthesis." The control group prompts for the implementation data survey every 2 mo merely asked them to respond to an open-ended question regarding which concepts they had mentioned about photosynthesis and cellular respiration and in how many classes. Therefore, the request for data itself became a part of the SUN intervention with regard to long-term, but not short-term outcomes. The last request for online data deposition occurred 3 mo before teachers took the test in August of 2010. Teachers did not receive such prompts during the workshop, and conclusions regarding the immediate effects of the workshop are therefore not affected.

It is possible that specific recall of the wording of an online survey prompt (through inadvertent teaching to the test) helped to define the choice for one test item and narrow the choice for another. Note, however, the months between the prompt and the test. In the most egregious case, "Law that usable energy is lost with each transfer" is a prompt for online data that closely approximates the correct response among four choices to the test question "Which of the following statements about energy is true?" The correct response is "Some usable energy is converted to an unusable form with each transfer." Those questions will be pruned as we increase the difficulty of items in future studies. Given the construction required to respond to the drawing assessment, those long-term significant effects are perhaps a more informative indicator of long-term learning, but the content is more specific. The process of asking teachers to monitor concepts taught may in fact be a strategy for long-term retention of ideas presented during professional development, but that question was not asked during this study. The survey prompts were considered necessary to document implementation of the intervention.

Discussion of Teacher Self-Efficacy Effects

The data show that treatment group teachers currently teaching regular biology who attended the SUN workshop also significantly improved their overall self-efficacy regarding the teaching of biological energy transfer relative to the randomly assigned controls (Figure 9). Similarly, their confidence in their knowledge increased significantly (Table 7). Interestingly, their belief in their ability to teach these topics as indicated by the PSTE subscale improved even further after using the SUN materials and attending two professional development meetings during the following year (Table 6).

Before the 2009 workshop, the SUN treatment and control group teachers had a similar overall self-efficacy and confidence in their knowledge, which was significantly lower than that of the AP pilot group. However, the overall self-efficacy mean scores (out of a possible 125 points) of the SUN treatment group who attended the workshop, even a year later, were similar to the mean scores of the incoming AP pilot group (treatment group year-later mean = 94.2 ± 7.6 vs. AP pilot group preworkshop 2010 mean = 93.1 ± 4.2; Figure 9).

Similarly, their confidence in their knowledge, as indicated by their confidence in each response on the multiple-choice exam on a number-line scale from 1, not at all, to 5, extremely, rivaled that of the preworkshop mean of the AP pilot group (treatment group year-later mean = 4.3 ± 0.5 vs. AP pilot group preworkshop 2010 mean = 4.3 ± 0.4; Table 7). This trend was already seen with regard to learning effects.

When the control group and the AP group attended the workshop in 2010, their scores also improved significantly on the overall measure of self-efficacy and the confidence in their answers. Even the AP pilot group of teachers increased their average confidence from "very confident" (4.3 ± 0.4) to "extremely confident" (4.9 ± 0.1) as a result of the workshop.

The only nonsignificant improvement was that of the AP pilot group with regard to the PSTE subscale after attending the workshop. The mean score change from 50.3 ± 3.4 to 54.6 ± 3.8 out of a possible 65 points had a p value of 0.07 and may reflect the small sample size (Table 6).

The changes in both confidence in their answers and self-efficacy as a result of the SUN intervention are evident in teachers' responses to the question "What has participation in the SUN Project meant to you professionally?" posed 1 yr after the SUN workshop. The most frequently used words by rank order were: students (1.42%), understanding (1.29%), energy (1.03%), and confidence/teaching (each 0.90%).

Similarly, enhanced teacher self-efficacy is reflected in comments teachers from all groups made when they were videotaped during the debriefing immediately after their classroom visit in year 2 of the study. By this time, all had brought the SUN materials into their classrooms. Teachers commented on their increased confidence in their own knowledge; the fact that they had effective materials to use in the classroom, which they had not previously had; and their expectations that students could learn the materials. The comments below by both regular and

AP biology teachers and other selected comments can be found on the SUN Project Web pages at www.msoe.edu/academics/research_centers/sun/signup.shtml.

> Teacher #1. "It's really impacted my, my [*sic*] teaching in that I'm excited about these concepts that I really was never excited about . . . because they're not that hard really."

> Teacher #2. "It's given me a deeper understanding." She also said, "They really did learn from the hands-on materials."

> Teacher #3. "Much easier for the kids to put a difficult concept into their head.. . . The hands-on manipulation allowed them to get a better idea" With regard to herself, she said that she was more creative and was using models when teaching other part so of the curriculum, "Rather than me showing you on a piece of paper, I said, 'You guys build it, you move it around and you show me why it works or it doesn't work.' "

> Teacher #4. "It has given me ways to get across abstract ideas . . . they seemed to have a better handle on how it worked.. . . I think the hands-on manipulation allowed them to get a better idea if they are a kinesthetic learner. Visually they were able to see it working and then they also had to explain it to somebody else, so then it brought an auditory portion of it. So I think they were using all parts of their brain to try and get an idea of what was going on."

> Teacher #5. "I never had this kind of information to teach this stuff. So it's given me more confidence like [*sic*] to teach AP biology. Now it's like I can get this stuff and I think I can teach it and I can bring it to a higher level now. I think I can make my kids understand and really guide students to understand this stuff . . . And of course then being in the project—the tools to do it."

> Teacher #6. "It has made me confident about the content."

> Teacher #7. "I feel so much more confident and comfortable teaching it." She also stated, "The kids really respond to it."

> Teacher #8. "It has allowed me to understand the process of photosynthesis and cellular respiration much better.. . . When the kids were working with the manipulatives, that [*sic*] they were getting and understanding it and enjoying it."

Therefore, the SUN workshop and continuing professional development program has demonstrated long-term effects by means of multiple measures, bringing regular biology teachers up to the level of AP teachers in terms of both knowledge and self-efficacy. It is noteworthy that for these experienced teachers, their personal confidence in their ability to teach these topics improved during the intervening year of classroom practice (Table 6). While the effects of the semiannual meetings and other continuing professional development cannot be disentangled, this result confirms what Palmer (2006) predicted as a result of his work with preservice teachers.

Future Plans

We now have the opportunity to more carefully align our materials with the model-building progression described in Figure 1. Because we have only recently become aware of the literature regarding analogical scaffolding through blended representations, we will review our materials in light of these findings (Podolefsky and Finkelstein, 2006, 2007b). The cross-cutting energy principles recently articulated as important national educational goals (U.S. Department of Energy, 2012) require *explicit* use of the universal laws of thermodynamics. Common language specified by our learning progression emphasizes the first law of thermodynamics, conservation of matter and energy, with learners describing the reactants and products for each process and where free energy is stored at the beginning and end of each process. Similarly, attention can be drawn explicitly to the second law of thermodynamics, that some free energy must be converted to an unusable form with each transfer and that therefore the end of the process stores less usable energy than what was present at the beginning (Figure 1, large blue box). The manipulatives also allow learners to experience conservation of matter when noting how matter is rearranged after electrons move. While we used all of this language in the previous workshop, based on recommendations from Eisenkraft and colleagues from the University of Massachusetts at the recent 2012 National Science Teachers Association meeting (Eisenkraft, 2012), we are currently revising materials so as to more *explicitly* define application of both the first and the second laws of thermodynamics to each experience.

As stated by Catley and colleagues (2005), "Big ideas are generative. They define a grammar of the discipline, not a simple collection of ideas" (p. 3). The large knowledge effect sizes reported here for the treatment group a full year after the SUN workshop versus the 2009 prescores of the randomized control group ($d = 1.91$ for the drawing with explanation assessment and $d = 0.94$ for the multiple-choice content exam) provide evidence that the SUN approach works and that knowledge gains are sustained. This evidence suggests that approaching biological energy transfer from the perspective of the work that can be done by moving electrons and the common language involved (Figure 1 and Table 1) provides a useful heuristic for teachers to learn this difficult topic. This approach allows teachers to consider why food and oxygen are essential for *our* lives but might not be needed for the microbes we are currently looking for on Mars (Chang, 2012). Considering energy transfer in terms of ultimate electron donors and acceptors can facilitate conversations about microbes that "eat" rocks (Newman, 2010) or about photosynthetic organisms deep in the ocean that use black-body radiation from a thermal vent as a source of photons (Beatty *et al.*, 2005). The recent article about personal fuel cells from snails becomes intelligible, with its description of one electrode for the electron donor and one for the electron acceptor (Halámková *et al.*, 2012). It might be interesting to see whether teacher understanding that life is powered by moving electrons facilitates student understanding that life itself depends on physical laws.

The long-term effects on teacher knowledge and self-efficacy and the initial equivalence of the randomly assigned teacher treatment and control groups suggest this trial is well positioned to provide meaningful data regarding the downstream impact of the SUN intervention on high school biology students (unpublished data). With National Science Foundation (NSF) funding, we are currently developing a SUN Chloroplast e-book and adapting the SUN Project materials for a variety of undergraduate courses.

ACKNOWLEDGMENTS

The research reported here was supported by the Institute of Education Sciences (IES), U.S. Department of Education, through grant R305B070443. We appreciate the opportunity to do this work made possible by federal funding and the guidance of retired IES program officer Dr. Harold Himmelfarb. The opinions expressed are those of the authors and do not represent views of the U.S. Department of Education. We thank undergraduate research assistants Ian Ashton, Heather Bobrowitz, Linnea Elliott, Kari Renzelman, Elise Pinkerton, Lindsey White, Anthony Gray, and Benjamin Blair for production of SUN materials within the MSOE Center for BioMolecular Modeling (CBM). The CBM is directed by Dr. Tim Herman, who contributed to a cytochrome *c* activity. We appreciate Mr. Ashton's help in engineering the ATP synthase model and Ms. Bobrowitz's development of a microbial fuel cell given to all participants. We also appreciate Professor Ray Arvidson of Washington University's remote presentation about Mars at the 2009 workshop. We thank the SUN scientist advisory board for their contributions to this project: Professors Rick Amasino (who has emphasized the e^- donor and acceptor in his teaching for years), Patrick Masson, and Ching Kung, as well as Drs. Michael Patrick, Michelle Harris, Jean-Yves Sgro, and Paul Williams of the University of Wisconsin–Madison and Professors Jim Mallmann and Mike Swedish, Dean Tom Bray, and Rich Phillips of MSOE. We are also indebted to Professor Bob Blankenship and Dr. Phyllis Balcerzak of Washington University, Professors Wen Luo and Carol Hirschmugl of University of Wisconsin–Milwaukee, and Professor Gul Afshan of MSOE for productive conversations. We thank Professor Andy Anderson of Michigan State University for access to his assessments. We especially thank Dr. John Finney, now retired from the Department of Veterans' Affairs, for helping to frame the original research design and for his ongoing support. We are indebted to the teacher participants for their evaluations of materials, suggested improvements, and faithful execution of the responsibilities for this project. Their interest and enthusiasm invigorated our work.

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