# Visualization of the Light & Dark Reactions of Photosynthesis Through Dynamic Demonstrations

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The blank stares of student faces whenever the words "our topic for today is photosynthesis" are uttered are disturbingly predictable. In our experience, there are several obstacles to presenting this material: boredom with a topic the students already know; a lack of understanding of the importance of the topic to the rest of biology; and simply the inability to see photosynthesis as a dynamic process.

Students are inundated with moving visual images at work, play and study. Lecturers present material in video, CD-ROM and computer animation formats in an effort to get students to look at the information. While these formats present material in a visually stimulating manner, they are by their nature passive, and students do not actively discover the process. This paper presents photosynthesis as a dynamic demonstration requiring student participation. The process of actively learning photosynthesis (or any other complex process) has been encouraged by the National Science Foundation as an improvement of pedagogy over standard didactic lecture (NSF 96-139). The demonstration described here is suitable for an advanced high school class (AP and IB) and can be expanded to include more detail for an introductory college class. This demonstration has been tested for four semesters with more than 100 students at the introductory college level (majors and nonmajors). The results have been encouraging. Students not only remember the process of photosynthesis, but they can describe it and draw inferences about what would happen if some essential part of the process is blocked or absent.

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The processes of photosynthesis can be depicted as sequential and are described here in that fashion. The demonstration is scripted in two Acts for 9–15 students. The minimum number (9) will work when Acts I and II are performed sequentially using the same students for both acts. Fifteen students are necessary to run the acts with different players. Acts I and II can occur simultaneously with cooperation of two groups of students and a large enough room. Either way you should make enough copies of the following script to hand out to the entire class.

## Photosynthesis

### (A dynamic demonstration in two acts)

**ACT I**
The Light Dependent Reactions

**CAST**
Sun
Water
Photosystem I (PS I)
Electron Transport Chain (three or more carrier molecules—ET I, II & III)
Photosystem II (PS II)
Thylakoid channel protein/ATP synthase complex (CP/ATP—can be two students attached together back to back)
NADP reductase (NADPred)

**PROPS**
A flashlight (solar energy)
Four small balls (excited electrons)
A jar of bubbles with bubble-wand (for production of oxygen)
Duplo™ or other large format snap-together blocks (square), labeled with permanent marker:
12-**ADP**—blue, 12-**P**—yellow;
12-**NADP**—green, 30-**H**-red
A table (the inside of the thylakoid)
A small bucket (the stroma)
3 × 5 inch notecards

Notecards can be given to each of the players so they know what to do, or the teacher may suggest that each group make its own notecards (Table 1).

**ACTION**
Arrange the students as shown in Figure 1 around the table. At a signal from the instructor the following sequence of events should occur:

1. The Sun turns on the flashlight and shines it at PS II.
2. The Water molecule releases two $H^+$ (red blocks) to the thylakoid (table), releases oxygen (blows bubbles), and passes an electron (ball) to PS II to represent the splitting of the water molecule.
3. PS II passes an electron (tosses a ball up in the air) to the first electron carrier in the electron transport chain (ET I catches the ball).
4. The electron carriers (ET I, ET II and ET III) pass the electron (ball) from one to another, each moving an $H^+$ (red block) from the stroma (bucket) to the thylakoid (table). The electron is finally transferred to PS I.
5. The Channel Protein/ATP synthase molecule (CP/ATP) collects two $H^+$ (red blocks) from the table and passes them to the stroma (bucket).
6. CP/ATP attaches a final Phosphate (yellow block) to the ADP (blue block) to make ATP. The ATP is also placed in the stroma (bucket).
7. The Sun shines the flashlight on PS I.

Table 1. Example text for character notecards for ACT I.

| *Character* | *Description* |
|---|---|
| SUN | Shines light (flashlight) on PS I or PS II. |
| PS I | Receives sunlight (flashlight); electron (ball) is released and captured by either ET I or NADPreductase. |
| PS II | Receives sunlight (flashlight); electron (ball) goes to ET I. |
| ET I | Receives electron (ball) from PS I or PS II and passes it to ET II. Takes $H^+$ (red block) from stroma (bucket) to the thylakoid (table). |
| ET II | Receives electron (ball) from ET I and passes it to ET III. Takes $H^+$ (red block) from stroma (bucket) to the thylakoid (table). |
| ET III | Receives electron (ball) from ET II and passes it to PS I. Takes $H^+$ (red block) from stroma (bucket) to the thylakoid (table). |
| CP/ATP | Takes two $H^+$ (red blocks) from thylakoid (table) and puts them in stroma (bucket). Makes 3 ATP by adding P (yellow block) to ADP (blue block) and puts it in stroma. |
| NADPred | Receives electron (ball) from PS I, takes one $H^+$ (red block) from stroma (bucket), and makes NADPH (red + green block) and leaves it in the stroma. |
| WATER | Gives electron (ball) to PS II, puts two $H^+$ (red blocks) in thylakoid (table), and releases oxygen (blows bubbles). |

8. PS I releases an electron (ball) to be captured either by the NADP reductase (NADPred) or ET I.
9. If NADPred catches the electron (ball), it takes an $H^+$ (red block) from the stroma (bucket) to make NADPH (green + red block). If the carrier molecule catches the electron, electron transport occurs again to produce ATP.

Steps 7–9 can be altered to omit the recycling of the electron (ball) until everyone has practiced the production of ATP and NADPH. However, our experience is that the competition for the excited electron enlivens this demonstration considerably.

**ACT II**

The Light Independent Reactions

**CAST**

3 RuBPcarboxylates (RUBISCO)
2 Phosphoglycerokinases or PGA kinases (PGK)
2 Diphosphoglyceroreductases or PGAP reductases (dPGR)
1 RuBPsynthase (RuBPsyn)

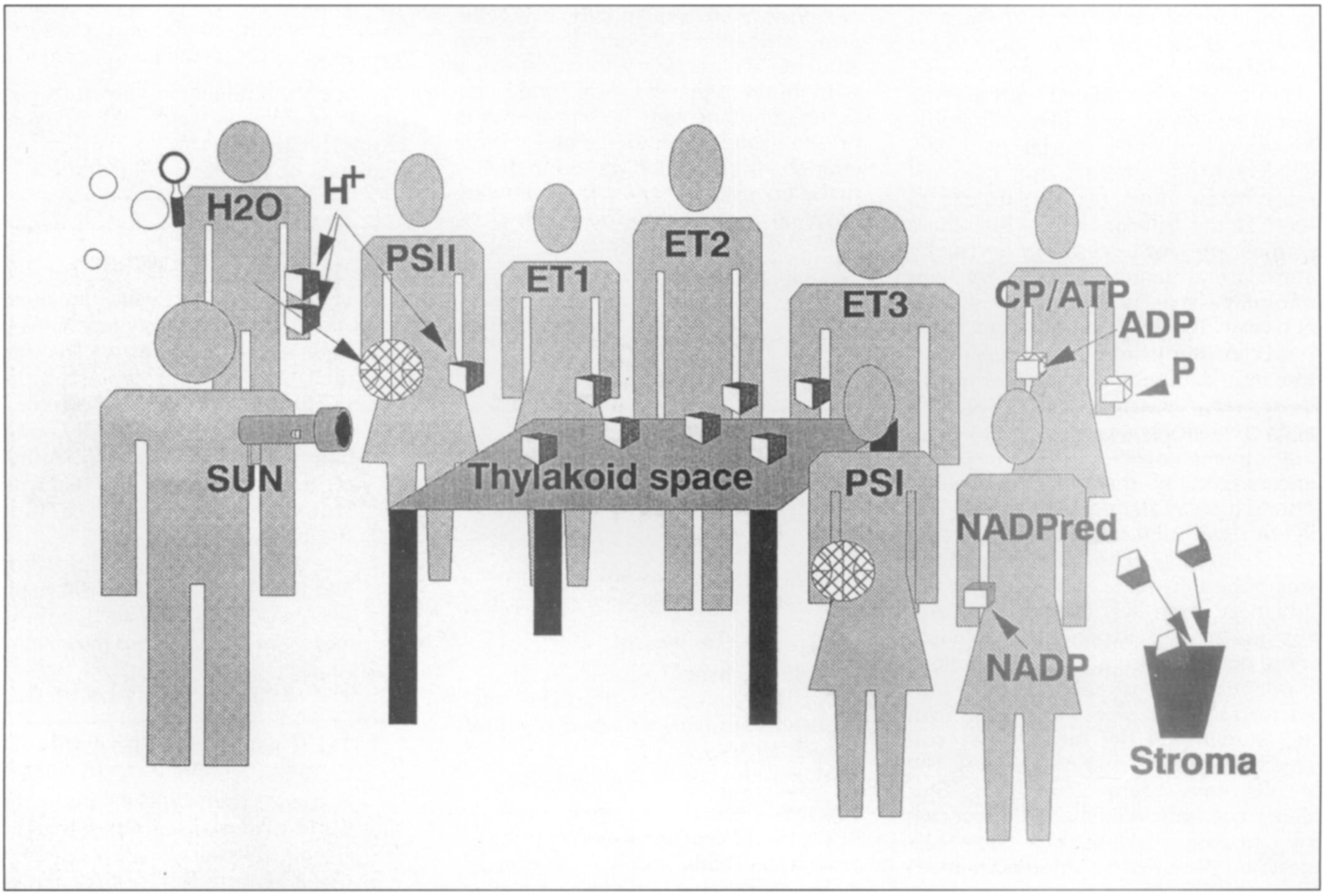


Figure 1. Arrangement of characters and props for Act I—Light Dependent Reactions. Characters: **SUN with flashlight** provides solar energy; **$H_2O$ with $H^+$ and bubbles** provides electrons, $H^+$ and $O_2$ to the system; **PS II** represents photosystem II; **ET 1, ET 2** and **ET 3** are the electron transport molecules; **PS I** represents photosystem I; **CP/ATP** is the Thylakoid channel protein/ATP synthase complex; and **NADPred** is NADP reductase. Small blocks represent molecules as labeled. **Stroma** is a repository or source for $H^+$, NADP, $NADPH_2$, ADP, P and ATP.

**PROPS**

21 green rectangular blocks arranged as three stacks of five blocks each (RuBP molecules)
4 green rectangular blocks (free $CO_2$s)
12 combination blue and yellow blocks (ATPs as formed in Act I)
12 combination green and red blocks (NADPHs as formed in Act I)
bucket (stroma)
3 × 5 inch notecards

Again, notecards can be given to each of the players so they know what to do or the instructor may suggest that each group make its own notecards (Table 2).

**ACTION**

Arrange the students as shown in Figure 2. The following sequence of events should occur at a signal from the instructor.

**Scene 1.** $CO_2$ FIXATION

1. Each RUBISCO, holding an RuBP (5 green blocks) finds a $CO_2$ (green rectangular block) and attaches this to the RuBP.
2. Each RUBISCO splits the resulting 6-carbon molecule into two PGAs (phosphoglycerates, 3 green blocks).
3. The PGAs (3 green blocks) are passed to the PGKs.

**Scene 2.** $CO_2$ REDUCTION

1. Each PGK transfers one phosphate (yellow block) from an ATP (blue and yellow) to the PGA he/she has just received. ATPs may be found in the stroma (bucket). The remaining ADP (blue block) is returned to the stroma.
2. The resulting PGAP (1,3 diphosphoglycerate, 3 green + 1 yellow block) are passed to the waiting dPGRs.
3. Each dPGR transfers one $H^+$ (red block) from an NADPH (green and red) to each of the PGAPs (1,3 diphosphoglycerate, 3 green + 1 yellow). NADPHs can be found in the stroma (bucket). The resulting molecules are PGALs (phosphoglyceraldehydes). Leftover NADPs (green blocks) are returned to the stroma.
4. One of the 6 resulting PGALs is dropped into the stroma (bucket); the remaining PGALs are passed to the RuBPsyn.

**Scene 3.** REGENERATION OF RuBP

1. RuBPsyn rearranges the 5 resulting PGALs (5 stacks of 3 green + 1 yellow + 1 red) into 3 RuBPs (3 stacks of 5 green blocks). Extra $H^+$ (red blocks) and phosphates (yellow blocks) are placed in the stroma (bucket).
2. Step 1 uses energy, so the RuBPsyn takes 3 ATP (yellow and blue) from the stroma and separates each into individual blocks. Return the resulting ADP and P to the stroma.
3. The resulting RuBPs are passed back to RUBISCO and the Calvin Cycle begins again.

Table 2. Example text for character notecards used in Act II.

| *Character* | *Description* |
|---|---|
| RUBISCO | Takes a $CO_2$ (rectangular green block) and attaches it to a RuBP (stack of 5 green blocks). The resulting 6 carbon molecule splits into 2–3 carbon PGAs (phosphoglycerate, 3 green blocks each). Pass the PGAs to the PGK. |
| PGK | Attaches a P (yellow block) from an ATP (blue/yellow block) to each of the PGAs. Passes resulting molecule PGAP (diphosphoglycerate, 3 green + 1 yellow) to the dPGR. The leftover ADP (blue block) is returned to the stroma (bucket). |
| dPGR | Transfers one $H^+$ (red block) from an NADPH (green + red block) to each of the PGAPs (diphosphoglycerates). The resulting molecules of PGAL (phosphoglyceraldehyde, 3 green + 1 red + 1 yellow) are passed to the RuBPsyn. The leftover NADP (green block) is returned to the stroma (bucket). |
| RuBPsyn | Drop one of the 6 PGALs into the stroma (bucket). Rearrange the other 5 PGALs into 3 RuBPs (3–5 block molecules into 5–3 block molecules). This uses 3 ATPs (break up three blue-yellow blocks) from the stroma. Return the ADP and P to the stroma. Left over $H^+$ (red blocks) and P (yellow blocks) are placed in the stroma. Pass the regenerated RuBPs to the RUBISCO. |

To run the demonstration simultaneously, refer to Figure 3 for the arrangement of the actors. The connecting feature between the two acts is the stroma. This is where ATP and NADPH are accumulated from the light dependent reactions and where phosphates, ADP, $H^+$ and NADP are released after the energy transfer takes place.

## Discussion

We have found that running the light reaction first, followed by the dark reaction, and then running them concurrently helps the students see the individual reactions and then realize their interdependency. To further their understanding of the interdependency, we have the students switch sides; those who were participants in the light reaction now assume the role of an enzyme in the dark reaction and vice versa. This can also serve to involve more students in a larger class, by rotating observers and participants. Finally, once the students appreciate the reaction, modifications or sophistications can be added.

The demonstration can be further sophisticated by adding a stomate character to regulate the supply of

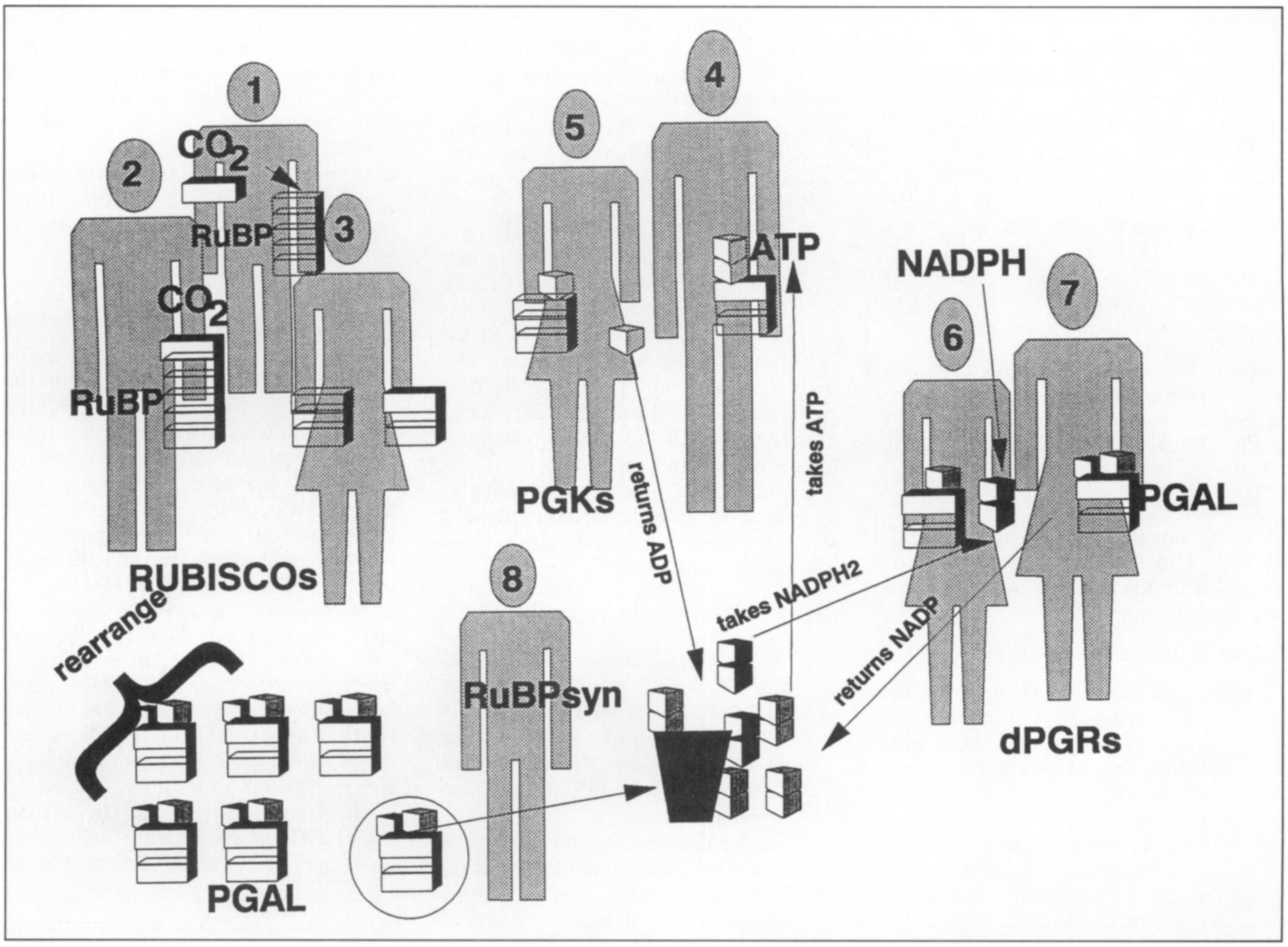


Figure 2. Arrangement of characters and props for Act II—Light Independent Reactions. Characters: **RUBISCOs** are RuBP carboxylates, **PGKs** are phosphoglycerokinases, **dPGRs** are diphosphoglyceroreductases, **RuBPsyn** is RuBP synthase. Characters are numbered in the order of the actions they depict. Rectangular blocks represent carbon molecules. Arrows represent movement of molecules.

$CO_2$. This character can also function to restrict the amount of $H^+$ available by limiting the supply of water. A further sophistication would be to restrict the intensity of light, or duration of light supplied. One mechanism for restricting duration is to employ a timer to tell the Sun character when to turn on the flashlight. The sophistications we have suggested can also be used to test the students' comprehension of the process. For example, the instructor can ask them to predict the amount of PGAL synthesized if the Stomate character is included, or what will happen if fertilizer or water is limiting. To test student knowledge of the overall reaction, a radioactive (marked) carbon dioxide or water molecule can be introduced. Students would then have to predict where the radioactive molecule will appear in the products.

We have also found the use of a computer simulation exercise (e.g. *Biology Explorer: Photosynthesis*, Logal Software Inc.) immediately following this demonstration to be helpful in reinforcing the concepts and steps in the processes.

## Conclusion

The entire demonstration underscores the dynamic nature of photosynthesis and helps students focus on the interdependency of the light dependent and independent reactions. The students who have participated in this demonstration in our classes actively encourage the other participants to do their jobs. For example, when dPGR doesn't have any NADPH, he/she politely informs PS II to increase its productivity. Students also frequently catch mistakes made by other students, such as making ATP when the light is not shining. By experiencing shortages of raw materials or energy, the students connect the process with the supply of materials present in the environment and the plant's ability to produce carbohydrates. We feel that this demonstration makes a complex process understandable and entertaining without leaving out important details. Furthermore, since the students are active participants in the process, they learn more effectively and more quickly, as evidenced by the ability of our students to answer more difficult and complex questions about photosynthesis on exams.

## References


NSF 96-139. (1996). *Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering and Technology*. Melvin D. George, Chair, Committee on the Review of Undergraduate Education.

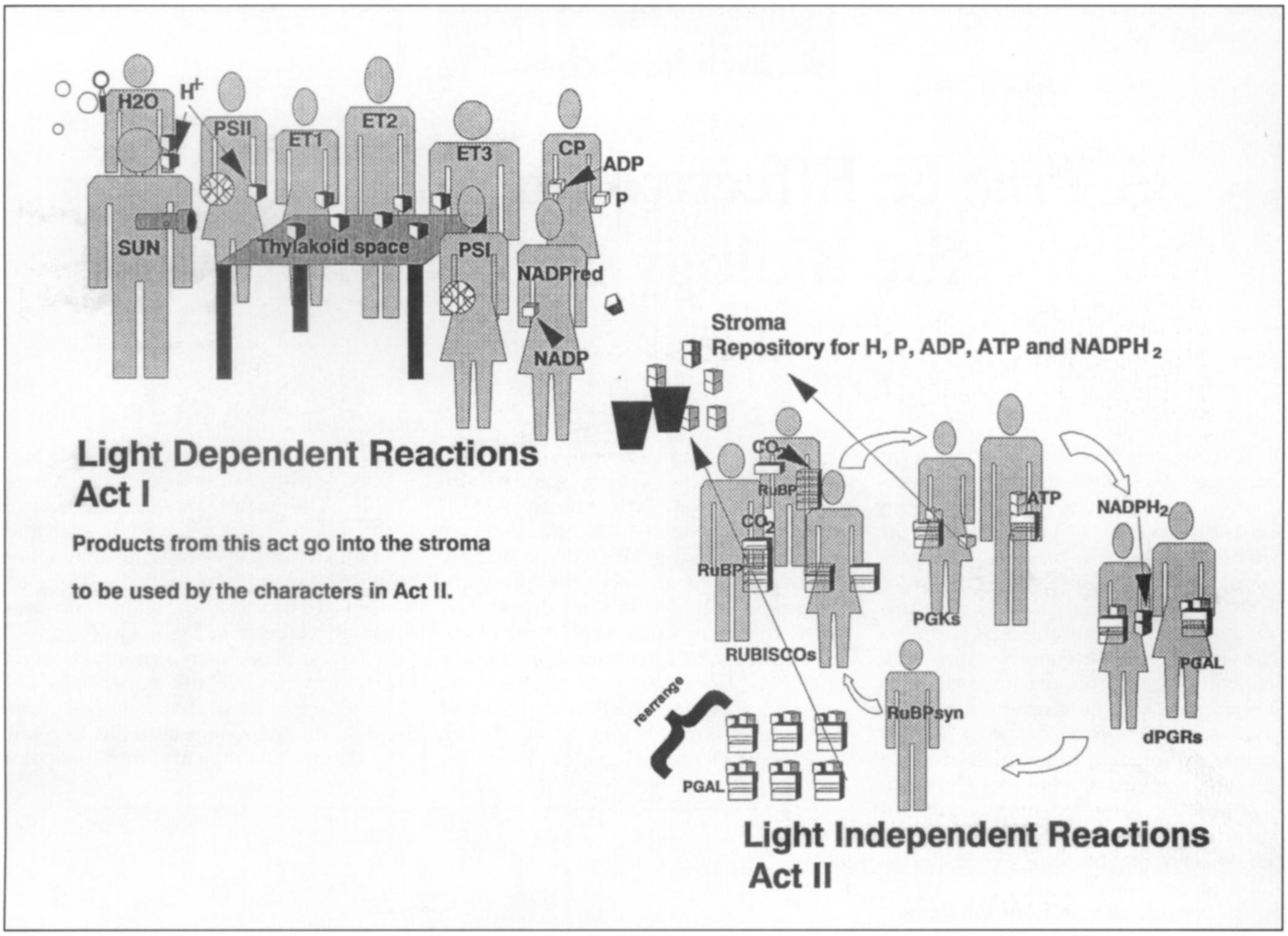


Figure 3. Suggested arrangement of characters and props for runnings Acts I and II simultaneously. Curved arrows represent the direction of movement of carbon during the light independent reactions. All characters, arrows and blocks are described in Figures 1 and 2.