SOLAR FOOD

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SOLAR FOOD: An Exploration of Photosynthesis

Teaching Guide

HRM SOFTWARE

SOLAR FOOD:

AN EXPLORATION OF PHOTOSYNTHESIS

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AN EXPLORATION OF PHOTOSYNTHESIS

Contents

I. INTRODUCTION

This teaching guide offers instructions on use of the program, a description of principles and assumptions underlying the program, learning objectives, auxiliary study suggestions and questions, work sheets suitable to reproduce for student use, and a bibliography.

A. General Content & Structure of Program

Almost all creatures on Earth ultimately depend on the sun to supply the energy needed for life. Photosynthesis provides the vital link between radiant energy and usable fuel sources. SOLAR FOOD explores this fundamental life process through animated visualizations of chemical reactions, interactive inquiry, and open-ended experimentation.

SOLAR FOOD consist of 3 major parts, each with a different approach to the presentation of material:

Part 1: Introduction and Tutorial Quiz
Part 2: Molecular Labelling Experiment
Part 3: Reaction Variables

Each section is self-contained, but when used in sequence, the sections build a logical progression from general concepts (Part 1), through details of the light and dark reactions (Part 2), and finally to experimentation with variables (temperature, light, CO_2) that affect the photosynthetic process (Part 3).

A HELP/REVIEW section, augmented with a GLOSSARY of key terms and abbreviations, can be accessed from any part of the program. A detailed explanation of the use of each part of the program is found in Section IV (p. 8) of this guide.

B. Target Audience

SOLAR FOOD may be used for students who are studying photosynthesis for the first time as well as for those who are ready to explore photosynthetic reactions and the interrelationships in more detail. It is appropriate for students at the high school and introductory college level. Some rudimentary knowledge of chemistry is needed, although most concepts are described at a fairly basic level in the HELP/REVIEW and GLOSSARY sections.

The three sections provide flexibility for a variety of classroom and individual instructional uses.

II. LEARNING OBJECTIVES

1. To emphasize the importance of the photosynthetic process.

2. To provide a review of basic facts and principles of photosynthesis.

3. To help students separate the photosynthetic process into the individual steps which lead to sugar production: in particular, to distinguish between the light and dark reactions.

4. To focus attention on the path of energy (electrons) through the various steps.

5. To help students understand the detailed reactions in the overall process.

6. To provide elementary experience with the design of scientific experiments to test specific hypotheses.

7. To help students understand how different variables (temperature, CO_2, concentration, water, etc.) can affect photosynthesis.

III. ASSUMPTIONS UNDERLYING THE PROGRAM

Photosynthesis is a complex process carried on by a variety of species. In order to focus this instructional program on key ideas in ways easily understood by students, a number of simplifications have been made in the presentation of material.

A. Eucaryotic Versus Procaryotic Processes

Photosynthesis occurs both in procaryotic organisms (certain bacteria) and eucaryotic organisms (algae, certain protozoa, and most plants). The events depicted in SOLAR FOOD are most typical of photosynthesis in green cells of higher plants.

B. ATP Production

For the sake of simplification, particularly with regard to the graphic animation of reaction steps shown in Part 2, no mention is made of cyclic photophosphorylation. In this reaction, the production of ATP from ADP and inorganic phosphate is coupled to the flow of excited electrons from photosystem 1 through a transport chain and back to the same photosystem, in a cyclic manner. This process occurs concurrently with the non-cyclic production of ATP and NADPH (which are depicted in the program). The electron carriers in the transport chain, with the exception of cytochrome b_6, serve both functions.

Furthermore, no discussion of pre-existing levels of ADP (and NADP) is given in the program. Students may need to be told that these molecules serve a wide variety of functions and are present in all cells. In Part 3, assessment of reaction rate assumes that the levels of these pre-existing compounds (along with all unspecified reaction conditions) are optimal.

C. Electron Transport

The program makes no distinctions between the light absorption charateristics of photosystems 1 and 2. In reality the two photosystems differ with regard to which wavelengths of light are best absorbed. Because of this difference, the relative effect of a particular wavelength of light would vary for ATP versus NADPH production. In the program, light is assumed to be of equal intensity across the visible spectrum, and production of ATP and NADPH is collectively used as an indicator of the rate of the light reactions.

The electron transport systems are described empirically, but there is no discussion of their individual components. For simplicity, the transfer of energy along the chain is demonstrated in the animation (Part 2) only as the transfer of electrons. Actually, in some cases the transfer is in the form of a proton plus its electrons. Reduction of NADP to NADPH (shown as NADP + H) follows this pattern.

D. Radioactive Isotopes

The molecular labelling experiments in Part 2 make use of radioactive isotopes, as is often the case in actual lab work. The isotope of oxygen used for labelling is ^{18}O, a stable but "heavy" isotope. In the program oxygen is treated as though the isotope is unstable (radioactive). Because ^{18}O is actually used as a molecular tracer, the concept of following oxygen through the photosynthetic reactions is valid. For simplicity, this isotope is shown as a flashing symbol along with the radioactive isotopes.

Scientists lack the advantage of a radioactive "cursor" for incorporation of radioactive isotopes, so some discussion about the nature of isotopes, their use, and their detection in the laboratory might be desirable. (A brief definition is offered in the GLOSSARY.)

A particular difficulty arises when hydrogen is used as the radioactive tracer. Protons exchange readily in an aqueous environment, and hydrogen is widespread, so there are many molecules which in theory could obtain this label. The "correct" predictions given in the Molecular Labelling Experiment are the molecules in which ^{3}H is most likely to appear.

E. Calvin-Benson Cycle

In the graphic animation pictured in Part 2, no details of individual steps of the Calvin-Benson Cycle are shown. In actuality, the cycle results in the synthesis of a six-carbon sugar using energy supplied by ATP and NADPH. In the animation, the timing of the oxidation and subsequent recycling of these high energy compounds are not intended to indicate anything about the sequence of their involvement in reaction steps.

Because the Calvin-Benson process is cyclic, the animation depicts the production of a molecule of glucose with each molecule of CO_2 fixed, i.e. with each round of the cycle.

This presentation assumes (as is true in nature) that the incoming carbon from CO_2 is attached to a pre-existing molecule of a five-carbon sugar. This sugar, called ribulose biphosphate (RuBP), is regenerated in the course of the reactions, resulting in a cycle. Six molecules of CO_2 are fixed to six molecules of RuBP to ultimately result in the net production of one molecule of glucose and regeneration of the six molecules of RuBP.

F. <u>Reaction Variables: Part 3</u>

The reaction conditions presented in Part 3 are not meant as a true simulation of photosynthesis in nature. Part 3 relies on a vastly simplified model of the process in order to let students discover a few of the relationships between different reaction components. Data for the reaction rates under various conditions are derived, after extensive simplification, from a sophisticated photosynthetic model created by G.D. Farquhar, S. von Caemmerer, and J.A. Berry.[1]

In reality, the production of sugar (overall photosynthetic rate) is less than might be expected based on the amount of ATP and NADPH supplied by the light reactions in many cases. The reason for this reduction in rate is that some of the high energy compounds are "wasted" through photorespiration, a reaction catalyzed by the same enzyme

[1] "A Biochemical Model of Photosynthetic CO_2 Assimilation in Leaves of C_3 Species," <u>Planta 149</u>: 78-90 (1980).

which fixes CO_2 for sugar production. Photorespiration is sensitive to the relative concentrations of oxygen and carbon dioxide. In SOLAR FOOD, photorespiration is ignored. Thus no distinction is made between C_3 and C_4 plants, which differ in this reaction.

Alteration in the reaction variables (hv, CO_2, temperature) are translated directly into an effect on the photosynthetic rate, without regard to the role played by stomata, leaf turgor, intercellular versus external temperature, etc. All these factors affect the rate in intact plants.

IV. USE OF THE PROGRAM

A. General Guidelines

1. Technical Information:

SOLAR FOOD is designed for use on the Apple II, II+, IIe, or IIc computer.

NOTE: If you are using the program on an Apple IIe or IIc, it is necessary to keep the "CAPS LOCK" key depressed.

The entire program is contained on a single diskette. Instructions for use are included within the program as well as summarized in Section B, "Summary of Sections."

2. Student-Program Interaction

SOLAR FOOD is a self-pacing exploration of photosynthesis. The length of time required to work through the program will vary considerably depending on each student's background and grasp of the material. First-time users will find it beneficial to work through the sections in sequential order. Students may find it useful to work through Parts 1 and 2 in one session and return at another time to Part 3. This section (REACTION VARIABLES) lends itself to repeated use.

Students may use the program individually or in small groups of 2 or 3. Group activity is especially appropriate for Parts 2 and 3.

3. <u>External Materials</u>

All the information needed to work through SOLAR FOOD is contained in the program itself. However, input from the instructor can provide a useful link between the material covered in the classroom and the learning opportunities offered by the program. Class discussions following individualized or small group interaction with the computer program will provide students with opportunities to compare and interpret their experiences.

The teaching guide includes sample work sheets (see Appendices C and D) which can be reproduced and distributed to students.

B. <u>Summary of Sections</u>

After booting the disk, the main menu will appear after the title page.

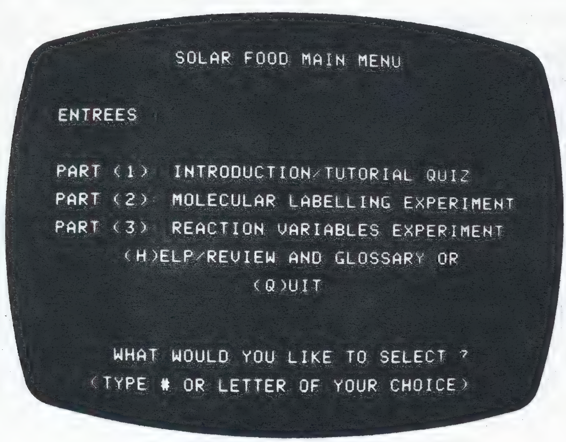

Figure 1

The HELP/REVIEW section briefly outlines basic facts pertaining to photosynthesis. Reading the REVIEW is optional, but students need to be comfortably acquainted with the information covered in this section in order to do the quiz (Part 1), to understand the animated version of the reactions seen in Part 2, or to work their way through the experiments with reaction conditions offered in Part 3.

The HELP/REVIEW can be accessed throughout the program by typing "H." When HELP is requested while in the TUTORIAL QUIZ of Part 1, the student is transferred to the section of the REVIEW which pertains to the specific question being attempted. From most other locations in the program, the student is transferred to a HELP MENU which lists the topics covered in the REVIEW, including the page of hints on using the program. The user can select a topic by typing its number or simply read through the entire REVIEW one page at a time. Pressing RETURN takes the user back to the HELP MENU. From the menu, the RETURN command takes the user back to the location from which HELP was requested. A copy of the text of the HELP/REVIEW is found in Appendix A; the screen of the HELP MENU is shown on the next page.

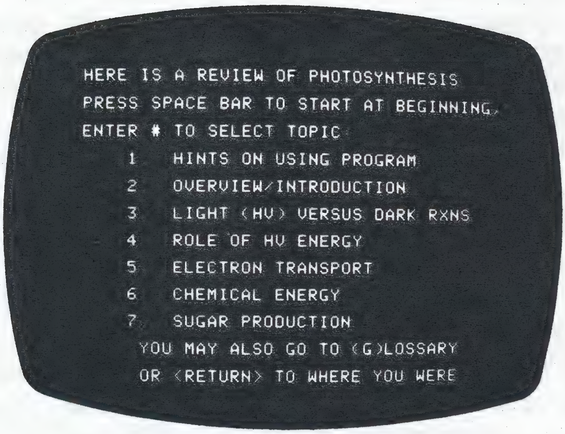

Figure 2

A GLOSSARY defining terms and abbreviations is included. The GLOSSARY can be accessed through the MAIN MENU or the HELP MENU. A copy of the text is given in Appendix B.

PART 1: INTRODUCTION AND TUTORIAL QUIZ

Part 1 offers a brief INTRODUCTION to the basic principles underlying the photosynthetic process, emphasizing these ideas with a simple animation. See Figure 3.

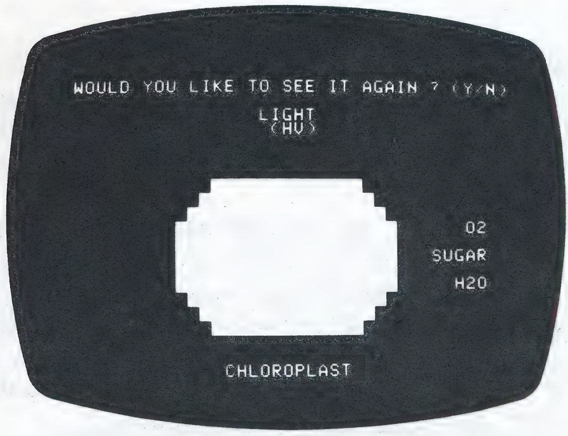

Figure 3

A TUTORIAL QUIZ follows. The QUIZ offers 10 questions about photosynthesis in a multiple-choice format. If a student selects an incorrect response, the computer responds with an explanation of why that answer is wrong and then allows the student to try again. At any question, a student can request HELP by typing "H" and be transferred to the appropriate part of the REVIEW (see discussion above for details). The program keeps track of the number of correct responses and the number of tries required to obtain them.

For students with a substantial knowledge of photosynthesis, the QUIZ serves as a quick review, and the working time in this section will be short.

Students with a limited background may wish to read the HELP/REVIEW before attempting the quiz, and they will require more time to complete Part 1. This part not only tests their knowledge, but also expands it through explanation of incorrect responses and reinforcement of correct answers.

For many students, it is useful to repeat the QUIZ after trying other parts of the program, especially after watching the animation in Part 2. This repetition provides a way to assess and reward learning. When re-entering Part 1, it is possible to bypass the animated chloroplast graphic by typing "?" as indicated.

PART 2: MOLECULAR LABELLING EXPERIMENT

Part 2 reinforces the students' grasp of reaction steps by helping them visualize the process. Animated graphics depict each of the major events.

Part 2 allows the student to follow the fate of individual atoms through the various steps. The concept for this section is analogous to isotopic labelling experiments actually carried out by biochemists. Students are given the opportunity to use radioactive isotopes to label individual atoms of key molecules involved in photosynthesis.

After choosing this section from the MAIN MENU, students can control a "radioactive" cursor. The cursor can be moved in four directions by pressing the I, J, K, or M keys. A Geiger counter responds with a clicking noise as the cursor approaches. The user moves the cursor out of this room to the "labelling lab."

In the lab the student is given the option to label one atom in the following molecules: H_2O, CO_2. The labelling is accomplished by moving the cursor over the letter representing the desired atom and then pressing the spacebar. Labelled atoms are indicated by a flashing letter.

Next, the student must predict in which molecules the labelled atom is expected to appear after going through the reactions. The student then watches the animation of reaction steps. A sample screen of the animation is shown below.

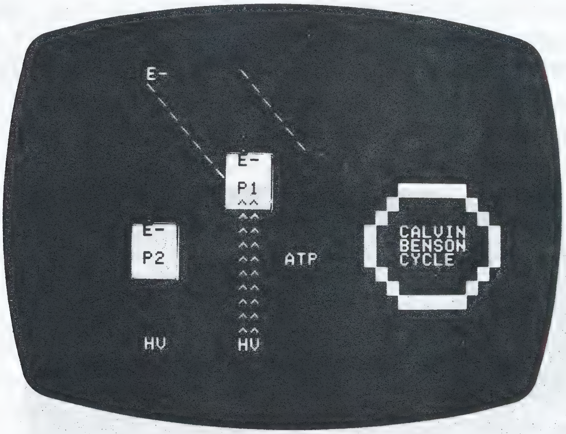

Figure 4

A line of explanatory text runs along the bottom of the screen. In re-running the animation or in subsequent experiments, the user has the option to go through the sequence with or without this text.

After the animated reaction has completed one cycle, the student is reminded of his prediction with regard to the label. The student can then repeat the reaction sequence with or without text, or he can label a new atom, again with the choice of watching the reaction cycle with or without text.

PART 3: REACTION VARIABLES

Part 3 is intended for students who already have a firm grasp of the material in Parts 1 and 2. Here, students have the chance to explore the relationships between various reaction components by altering reaction conditions and monitoring the effect on reaction rate. This part consists of 3 subsections: Questions, Experiment, and Sample Graphs.

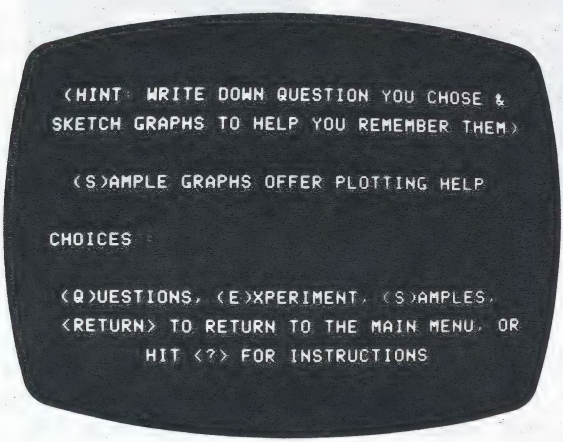

Figure 5

SAMPLE GRAPHS

Because the computer graphs the data they generate, it is important for students to understand the basic concept of graphing points. For those without much previous experience, a preliminary run through the SAMPLE GRAPHS section may prove useful. This auxiliary section of Part 3 provides examples of various types of graphs the students will encounter.

QUESTIONS

Once users are ready to design an experiment, the students should go to the list of QUESTIONS by typing "Q." This set of questions is not intended as a test. Instead, questions should be viewed as goals toward which to work. To scroll through the list of questions, the students use the keys marked with arrow symbols (<-- -->).

The students select the question to attempt first, decide what variables should be altered to obtain pertinent data, and then go to the EXPERIMENTS section to gather data. For clarity, it may be helpful to have the students copy down the question under consideration so that it can be consulted while doing the experiment. WORK SHEETS to record questions and sketch graphs are provided in Appendices C and D. A copy of the list of QUESTIONS is in Appendix E. Appendix F is a list of words that may be used as answers for the questions in Part 3. The program includes screen instructions on how to answer questions. These are shown in Figure 6.

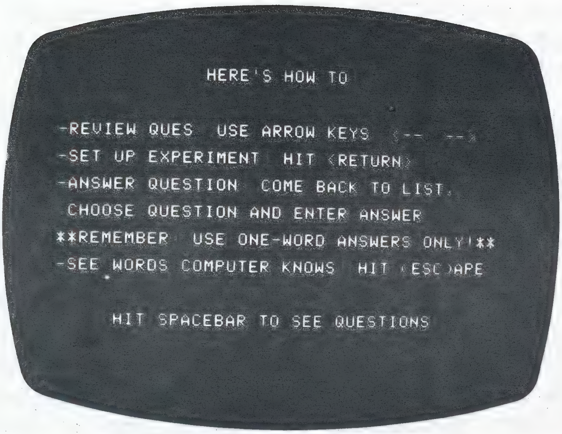

Figure 6

NOTE: While in the QUESTION section, students may type (?) to see the above instructions.

EXPERIMENTS

This section of the program is an open-ended exploration which provides the following opportunities:

1. To give students experience with the concept of scientific experimentation.

2. To help students understand how to interpret graphs in general and rate data in particular.

3. To provide insight into the fundamental relationships between reaction components in the photosynthetic process.

Once students enter the EXPERIMENTS section, they must make choices about which variable to alter, under specified conditions. Any condition not specified is considered to be at an optimal level.

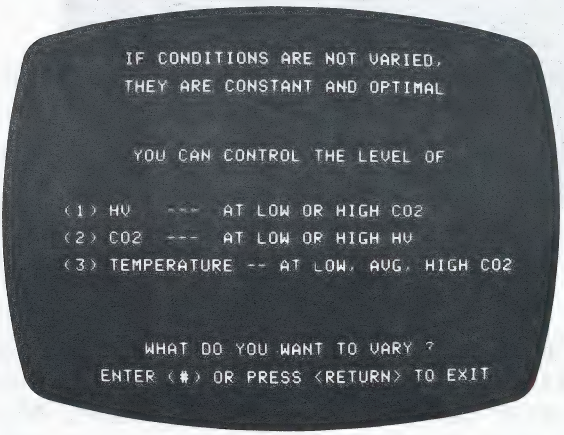

Figure 7

The students must also select how they want to monitor rate: as the rate of ATP & NADPH production (which reflects the rate of the light reactions) or by measuring production of sugar (reflecting the rate of the overall process.)

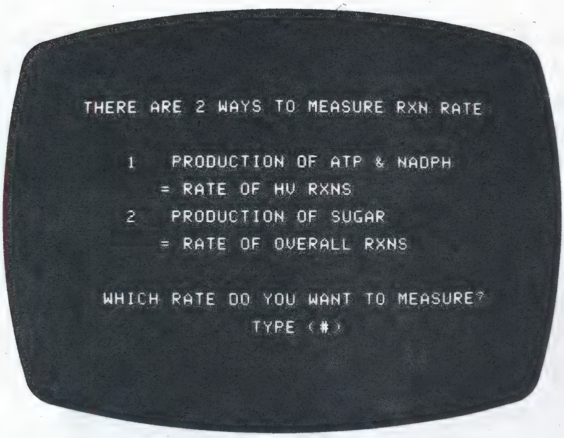

Figure 8

Students control the level of the chosen variable by entering numbers over the range being measured. To enter a number, they must type the number and then press the spacebar. The precise numbers and units used are much less significant than an understanding of the general behavior of the photosynthetic process as the variable is altered. When the students think they have selected enough points, they may instruct the computer to DRAW the curve by typing "D."

AND QUESTIONS AGAIN...

If the resulting graph is sufficient to make the answer clear, the students can now go directly to QUESTIONS, scroll to the question, select the question by pressing the spacebar, and then enter their answer. An answer is entered simply by typing the word and then hitting the spacebar.

NOTE: STUDENTS SHOULD USE ONE-WORD ANSWERS ONLY!

The computer recognizes a list of vocabulary words and indicates if the answer is correct (+) or incorrect (-). If an unknown vocabulary word is used, the computer indicates that another word must be tried. Students should be able to choose vocabulary without much difficulty, but a partial list of recognized words can be selected by pressing the ESCAPE key.

If the answer entered is incorrect, the student must exit the QUESTIONS section. They may then reconsult the current graph or generate a new one in search of the right answer. Only then can they re-enter QUESTIONS to try again. This procedure encourages the student to think rather than guess in answering.

No score is kept. The objective of the QUESTIONS is to guide the students in designing and interpreting experiments. Some questions are comparisons which require more than one experiment to find the answer. There is often more than one choice of experiments which can be used to obtain the needed data.

Students will probably work through only a few questions at a sitting. Only the best students are likely to find the solution to every question.

V. TOPICS FOR FURTHER DISCUSSION

Part 2: Molecular Labelling Experiment

1. Where does the sequence of events in the animation occur?

   ..in chloroplasts of green tissues of plants

2. What is the function of light in photosynthesis?

   ..splits water with the release of oxygen and an electron

3. Besides oxygen, what is produced in the light reactions?

   ..ATP and NADPH

4. Where do the ADP, P, and NADP you see in the animation come from?

   ..they are already in the chloroplast

5. When ADP and P join to form ATP and when NADP, an electron, and H join to form NADPH, what has happened?

   ..energy has been stored

6. What happens in the Calvin-Benson cycle?

   ..sugar and water are produced

7. In the Calvin-Benson cycle, what happens when NADPH is changed to NADP and H and when ATP is changed to ADP and P?

   ..energy is released to run the Calvin-Benson cycle

8. When it becomes dark, how long can the Calvin-Benson cycle continue after the light reactions have stopped?

   ..until the supply of ATP and NADPH runs out

9. If any one of these molecules is absent, the Calvin-Benson cycle will stop. What are they?

   ..ATP, NADPH, CO_2

10. In which end product does each of the following end up?

H in H_2O	..water, sugar, NADPH
O in H_2O	..molecular oxygen released from the chloroplast
C in CO_2	..sugar
O in CO_2	..sugar, water

Part 3: Reaction Variables

Appendix D includes questions in the program. Have your students discuss the data they collected to answer each one.

In addition, the following could be used as additional questions for classroom discussion. The students could also use them as the basis for exploring the experiments section of Part 3, in which case the discussion would run more smoothly if they have sketches of the graphs they ran.

1. As light increases, the rate of hv reactions is best shown by what kind of graph?*

   ..saturates at "X"

2. When CO_2 is the variable, as CO_2 is increased, the rate of the hv reactions is best shown by what kind of graph?*

   ..no effect

3. Which of the variables studied has no effect on the hv reactions?

   ..CO_2

4. When light is plentiful, how does the rate of sugar production at low CO_2 levels compare with the rate of sugar production at high CO_2 levels?

   ..up to 200 microbars of pressure, sugar production increases as CO_2 increases; above 200 microbars, sugar production levels off

* See Sample Graphs in the program for a description of different types of graphs.

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Appendix A

HELP/REVIEW

<u>Photosynthesis</u>: The sun's energy is captured by plants and transformed into chemical form where it is available as fuel for plants, animals, and micro-organisms.

Within green plant cells, the photosynthetic process occurs inside structures called chloroplasts.

The most important overall result of photosynthesis is the manufacture of sugar. The raw materials used are H_2O and CO_2. O_2 is given off as a waste product. But H_2O and CO_2 do not interact directly.

Instead, there are two major groups of reactions (RXNs): light (hv) and dark.

The main purpose of each set of reactions is:

1. hv RXNs put energy from sunlight into chemical form.
2. Dark RXNs use this chemical energy to produce sugar.

Light (hv) RXNs:

$$hv + H_2O + ADP + P + NADP + H \text{ ----> } ATP + NADPH + O_2$$

Dark RXNs:

$$ATP + NADPH + CO_2 \text{ ----> } ADP + NADP + SUGAR + H_2O$$

The sugar produced (GLUCOSE = $C_6H_{12}O_6$) provides a way to store energy originally obtained from the sun. When energy is needed, glucose is broken down to produce ATP, the "energy currency" of living systems. This process is cell respiration.

Changing hv energy to chemical form begins when pigments trap hv energy. Pigments in the chloroplast absorb visible hv to supply power for hv reactions. Chlorophyll A and accessory pigments form two photosystems, P1 and P2. Each photosystem acts as an antenna to absorb hv (light).

Hv energy is needed for exciting electrons in pigment molecules. Electrons (e-'s) energized by hv are released from chlorophyll A and pass along the electron transport chain.

Electrons (e-'s) pass from one molecule to another along the chain. In each step, electrons lose energy until they return to their original (unexcited) energy state.

The energy released is stored in high energy compounds, ATP and NADPH.

In the initial steps, energized electrons leave P2. The splitting of H2O (photolysis) supplies more electrons (e-'s) to replace those released by Photosystem 2 (P2). O_2 is given off as a waste product.

When electrons reach Photosystem 1 (P1), they require more hv energy to continue their journey. As electrons pass along the chain, energy released is used to form ATP and NADPH:

ADP + PHOSPHATE (P) ----> ATP

NADP + H ----> NADPH

These high energy compounds are the payoff of the hv reactions. They provide chemical energy needed to make sugar in the dark reactions.

The main purpose of the dark reactions is to make sugar (GLUCOSE = $C_6H_{12}O_6$). Dark reactions are driven by chemical energy stored in ATP and NADPH, which are made in the hv reactions.

In the dark reactions sugar is made through a series of steps, the Calvin-Benson Cycle. This cycle uses carbon from CO_2. In a series of reactions it builds up the six-carbon sugar, glucose. H_2O is released. Energy to fuel these steps comes from changing ATP back to ADP + P, and NADPH to NADP + H. These molecules are recycled back to the hv reactions for reuse.

Appendix B

GLOSSARY

ADP: See ATP.

ATP: Adenine trinucleotide phosphate. The third phosphate of ATP is attached by a high energy bond. When this bond is cleaved, energy is released and ADP remains. (ADP = adenine dinucleotide phosphate)

Calvin-Benson Cycle: Series of reactions in which CO_2 is added to a five-carbon compound to produce glucose.

chlorophyll: Green pigment which absorbs light in photosynthetic reactions. One type, chlorophyll A, is found at the center of the photosystems.

chloroplast: Organelle in green plant cells in which photosynthesis occurs.

electron transport chain: Series of molecules along which excited electrons pass as they release energy and return to their normal, unexcited energy state. Some of this energy is used to produce high energy compounds, ATP and NADPH.

glucose: six-carbon sugar ($C_6H_{12}O_6$).

hv: Abbreviation for "light." (You want to know why it's not "lt," right? Hv stands for the Greek letters physicists use to designate light.)

isotopes: Different forms of an atom which differ in physical properties, such as being radioactive.

NADPH: Nicotinamide adenine dinucleotide phosphate. This compound is produced when NADP accepts an electron (carried by hydrogen). NADPH contains a large amount of energy.

photolysis: hv-induced splitting of H_2O in the early steps of photosynthesis.

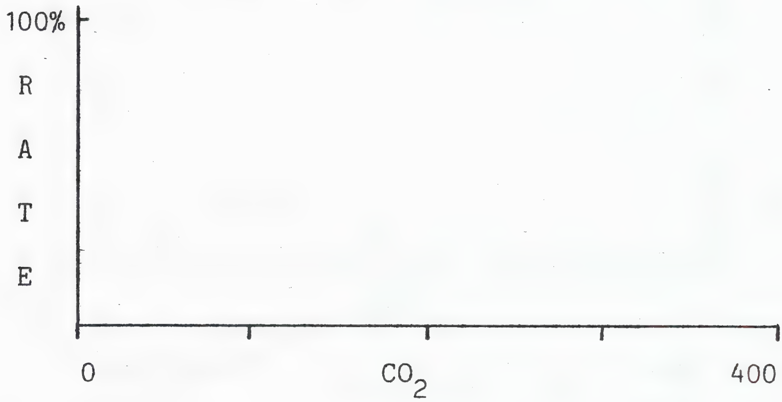
photosystem: A group of pigment molecules which act as an antenna to collect visible light used to power photosynthetic reactions.

respiration (cellular): The use of O_2, in a cell, to break down large molecules such as glucose to release energy.

RXNs: Abbreviation for "reactions."

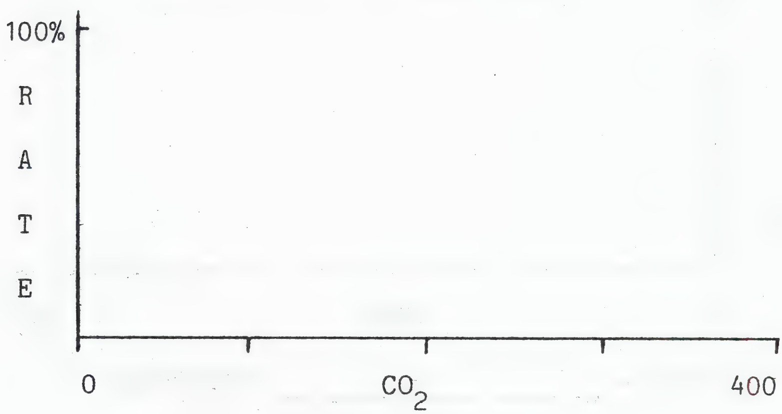
Appendix C: Altering CO_2

ALTERING CO_2 AT ________ HV



RATE = ______________________ PRODUCTION

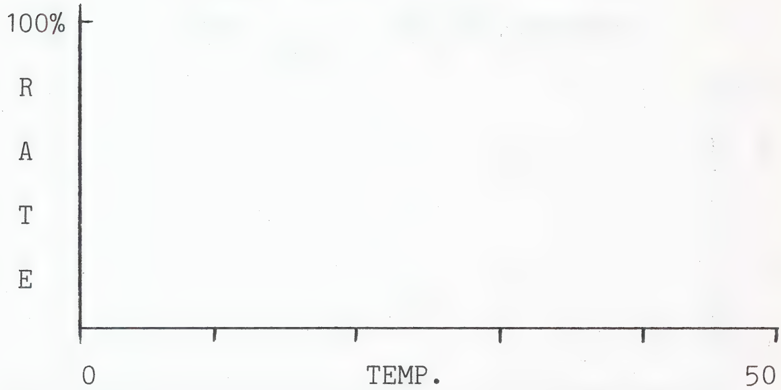
ALTERING CO_2 AT ________ HV



RATE = ______________________ PRODUCTION

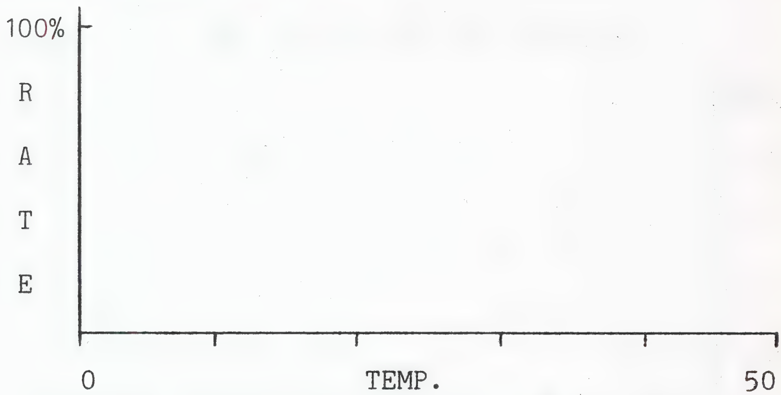
Appendix C: Altering Temperature

ALTERING TEMP. AT ________ CO_2



RATE = ________________________ PRODUCTION

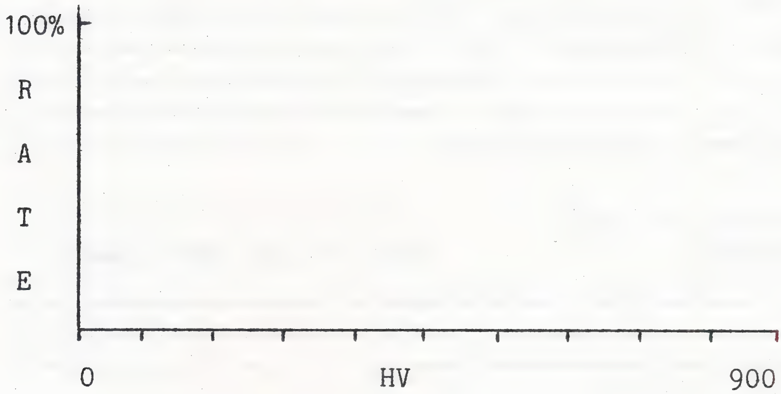
ALTERING TEMP. AT ________ CO_2



RATE = ________________________ PRODUCTION

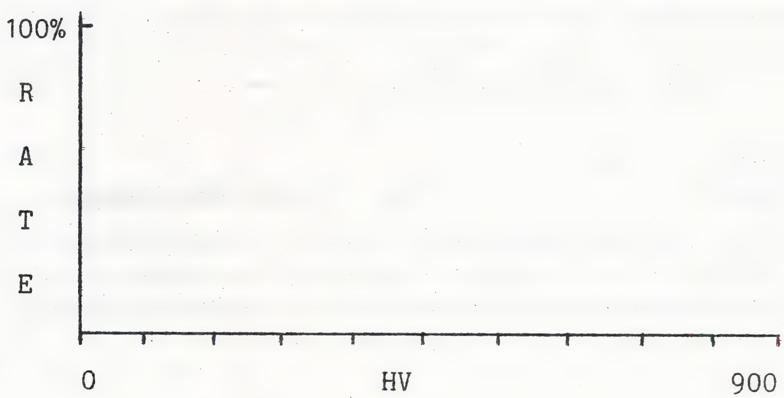
Appendix C: Altering hv

ALTERING HV AT ________ CO_2



RATE = ______________________ PRODUCTION

ALTERING HV AT ________ CO_2



RATE = ______________________ PRODUCTION

Appendix D

QUESTION WORKSHEET

Question: ____

____

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____

____

Experiments to try:

Variable | Type of Rate Measurement

____

____

____

Question: ____

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____

____

Experiments to try:

Variable | Type of Rate Measurement

____

____

____

Appendix E

QUESTIONS FROM PART 3

1. As hv goes from 0 --> 600 micromoles photons at high CO_2, what happens to rate of sugar production?

2. As hv goes from 600 --> 900 micromoles photons at high CO_2, what happens to rate of sugar production?

3. As hv goes from 0 --> 600 micromoles photons at high CO_2, what happens to rate of the hv reactions (ATP and NADPH production)?

4. When hv and CO_2 are plentiful, how does the rate of the hv reactions compare with the rate of sugar production?

5. As hv goes from 0 --> 100 micromoles photons at low CO_2, what happens to rate of sugar production?

6. When hv is plentiful but CO_2 is low, how does rate of the hv reactions compare with rate of sugar production?

7. As CO_2 goes from 0 --> 250 microbar pressure at low hv what happens to the rate of the hv reactions?

8. As CO_2 goes from 0 --> 250 microbar pressure at high hv, what happens to rate of sugar production?

9. When hv is plentiful, what effect does decreasing CO_2 have on the maximum rate of sugar production?

10. When hv is plentiful, what effect does increasing CO_2 have on the rate of hv reactions?

11. Assume photosynthesis is occurring at low levels of hv and 150 microbars CO_2. What happens to the rate of sugar production if CO_2 increases?

12. As temperature is raised, overall rate of photosynthesis: (1) always increases; (2) rises then falls; (3) falls then rises; (4) is unchanged... Enter #.

13. At high CO_2, what is the optimal (best) temperature for sugar production? Enter # in degrees centigrade.

14. At low CO_2, what is optimal temperature for sugar production? Enter # in degrees centigrade.

15. At constant temperature, what directly controls the rate of ATP and NADPH production?

16. What variable could be kept low such that the rate of sugar production would exceed the rate of hv reactions?

17. When CO_2 is varied at high hv, the rate of sugar production is shown by which kind of graph? (1) linear decrease; (2) saturates at X; (3) no effect; (4) minimal level... Enter #.

18. Changing the temperature has the greatest effect on the rate of the dark reactions at what level of CO_2? (1) high; (2) average; (3) low... Enter #.

Appendix F

WORD LIST FOR ANSWERING QUESTIONS (PART 3)

increases	decreases	H_2O
faster	slower	O_2
greater	smaller	CO_2
unchanged	same	$C_6H_{12}O_6$
constant	equal	hv
limited	fluctuates	temperature
peaks	none	ATP
nothing	identical	NADPH


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