Appendices

Appendix A. Diagnostic Question Cluster and student responses

Correct answers are indicated in green. Some questions have alternative stems (questions without distractors) that can be used with the same foils. Questions are presented in multiple-choice format, but can be used in multiple-true/false format. The stems from most of the questions can be used as prompts for essay questions. Altered stems are proposed for essay versions of the remaining questions.

Questions are categorized according to the practices demanded by the stem. They are presented in order of increasing complexity. The first four questions ask students to trace matter through the process of photosynthesis. Questions 5 - 9 involve tracing matter and keeping track of scale, since the questions are posed about whole organisms, but the explanations lie at the cellular level. Of these questions 5 – 7 address mass gain in plants, while question 8 and 9 address mass loss in plants. The latter requires that students understand that plants undergo respiration as well as photosynthesis. Questions 10 – 12 ask students about energy sources for plants without (questions 10 – 11) and while simultaneously keeping track of scale. These questions require students trace energy through both photosynthesis and respiration.

Tracing matter

1. H_2S Bacteria

Some bacteria can undertake a type of photosynthesis that uses H_2S in place of H_2O. Assuming that the process is otherwise similar to green plant photosynthesis, which of the following could represent the overall reaction?

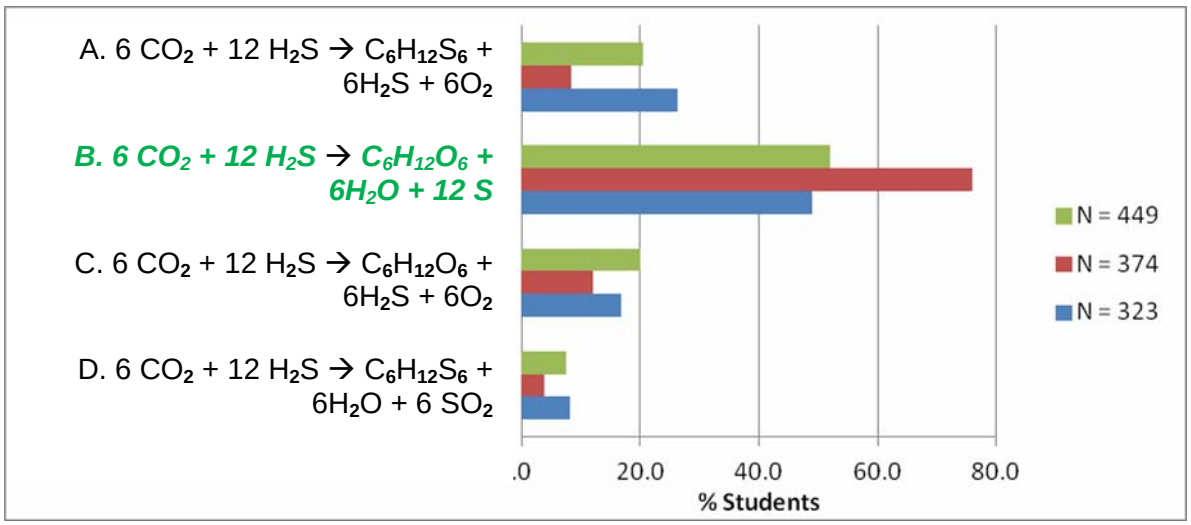
A. $6\ CO_2 + 12\ H_2S \rightarrow C_6H_{12}S_6 + 6\ H_2S + 6O_2$

B. $6\ CO_2 + 12\ H_2S \rightarrow C_6H_{12}O_6 + 6\ H_2O + 12\ S$

C. $6\ CO_2 + 12\ H_2S \rightarrow C_6H_{12}O_6 + 6\ H_2S + 6O_2$

D. $6\ CO_2 + 12\ H_2S \rightarrow C_6H_{12}S_6 + 6\ H_2O + 6\ SO_2$

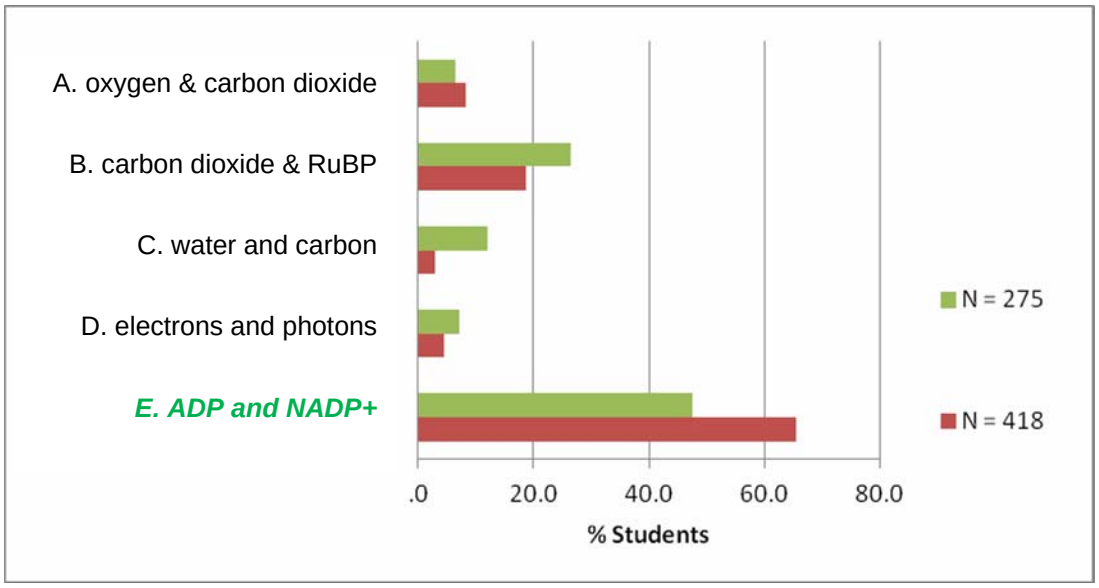
[Essay prompt: Assuming that the process is otherwise similar to green plant photosynthesis, complete the equation for the process: $6\ CO_2 + 12\ H_2S$ ->]



2. Products of the CC used by the light reactions

What products from the Calvin cycle are required for the light reactions?

A. oxygen and carbon dioxide
B. carbon dioxide and RuBP
C. water and carbon
D. electrons and photons
E. ADP and NADP+



3. Newly discovered organelle 1

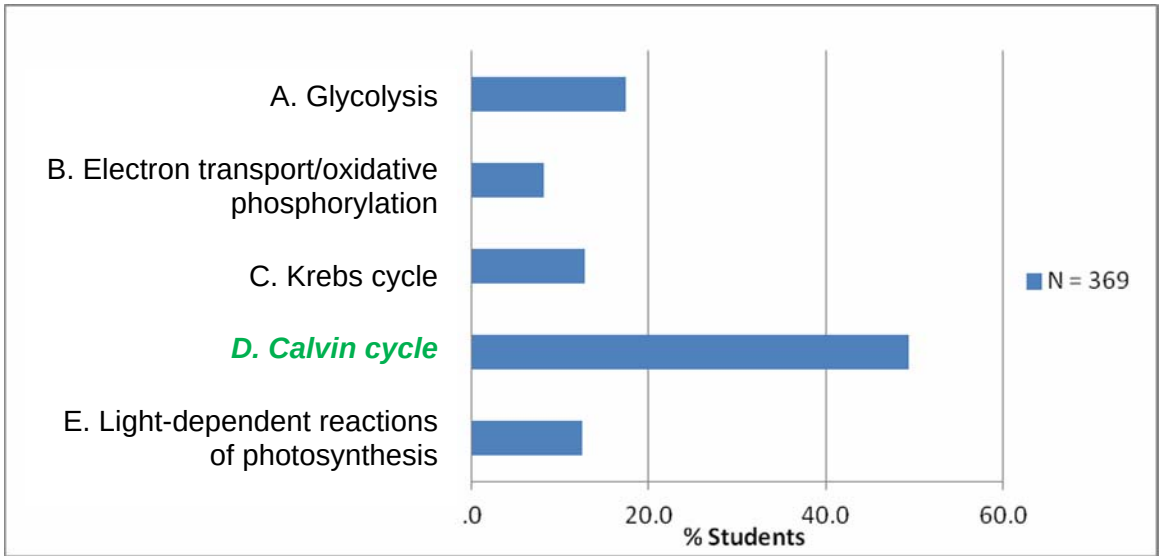
A newly discovered cell organelle is found to produce or use up the following molecules under experimental conditions:

Produce	Use Up	No Change
ADP + Pi	ATP	O_2

3-carbon sugars	CO_2	
$NADP^+$	NADPH	

Based on this analysis, which metabolic process is taking place in this organelle?

A. Glycolysis
B. Electron transport/oxidative phosphorylation
C. Krebs cycle
D. Calvin cycle
E. Light-dependent reactions of photosynthesis



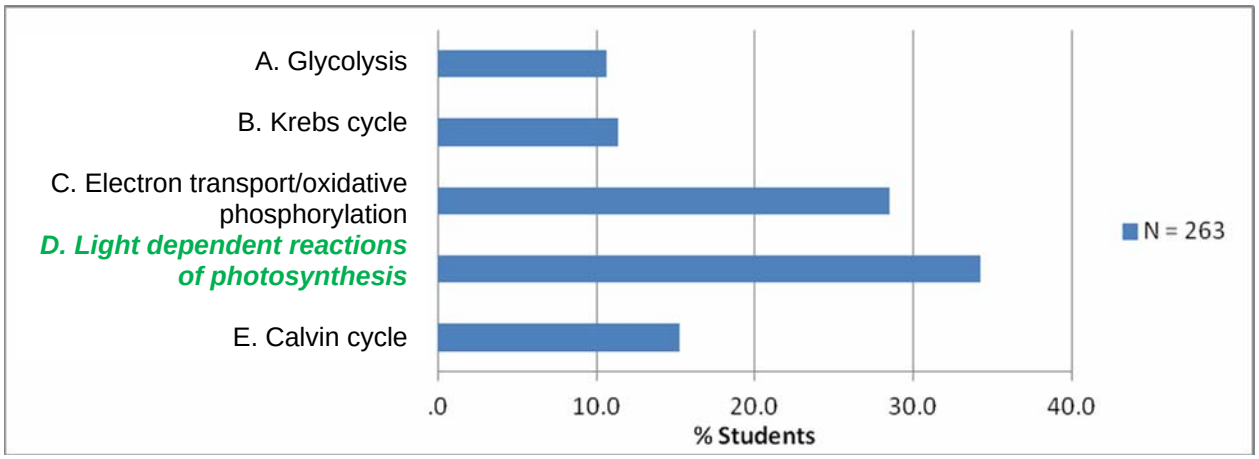
4. Newly discovered organelle 2

A newly discovered cell organelle is found to produce or use up the following molecules:

Produce	**Use Up**	**No Change**
ATP	ADP + Pi	CO_2
NADPH	$NADP^+$	3-carbon sugar
O_2		

Based on these data, which metabolic process is taking place in this organelle?

A. Glycolysis
B. Krebs cycle
C. Electron transport/oxidative phosphorylation
D. Light dependent reactions of photosynthesis
E. Calvin cycle



Tracing matter and identifying scale and location

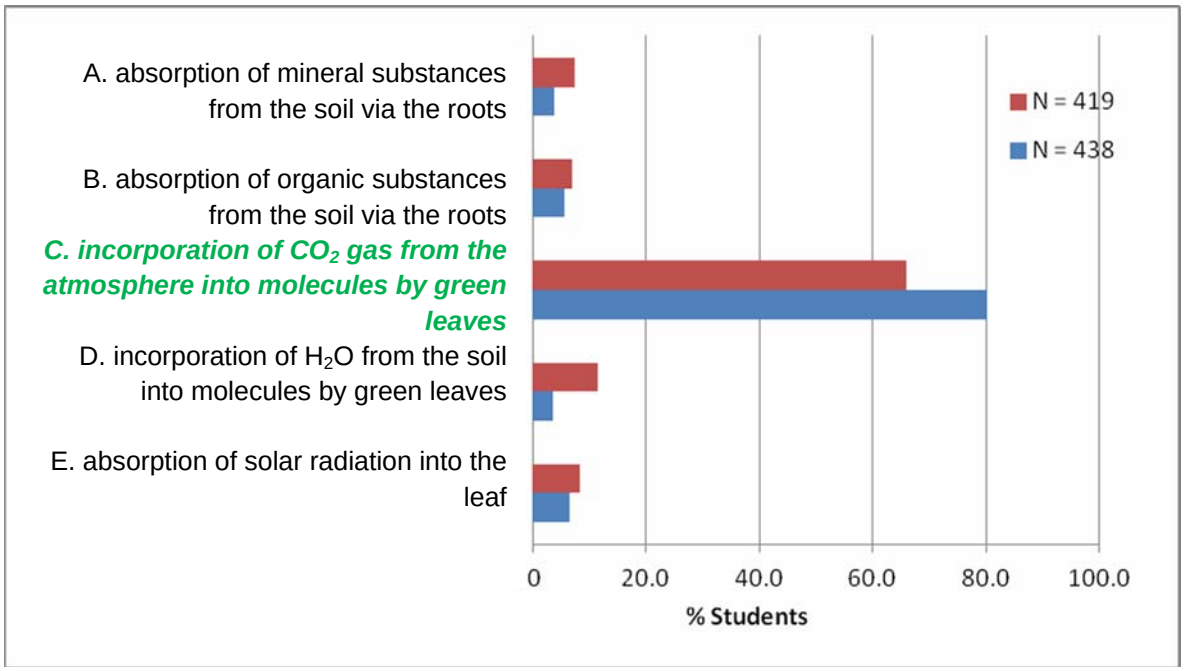
Mass gain in plants

All three questions (5 – 7) about mass gain in plants have the same distractors and essay prompt.

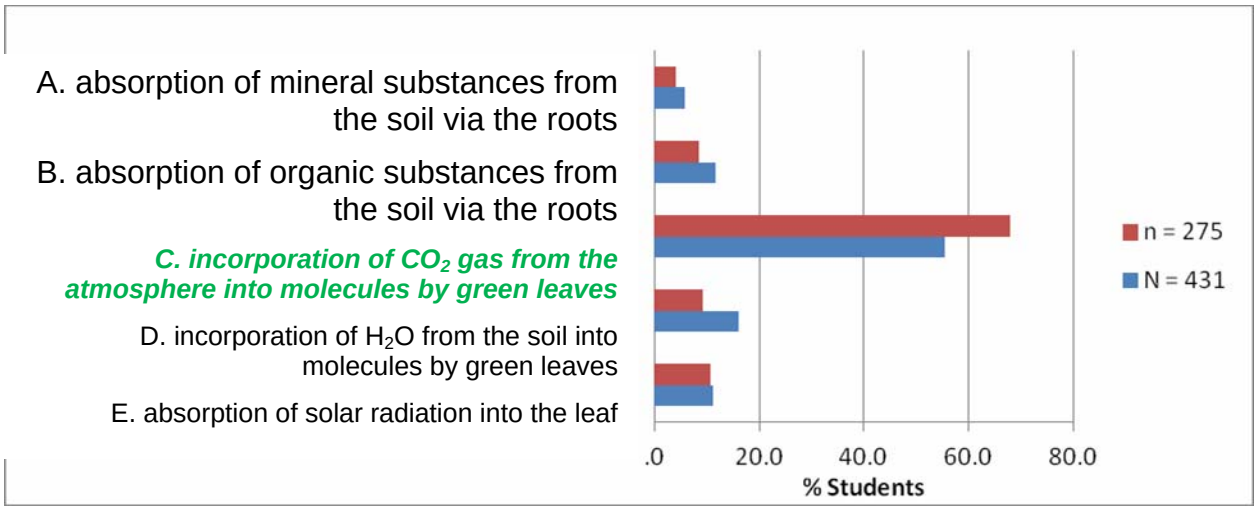
5. Maple tree (Based on an interview question from *Private Universe)*
A mature maple tree can have a mass of 1 ton or more (dry biomass, after removing the water), yet it starts from a seed that weighs less than 1 gram. Which of the following processes contributes the most to this huge increase in biomass?

A. absorption of mineral substances from the soil via the roots
B. absorption of organic substances from the soil via the roots
C. incorporation of CO_2 gas from the atmosphere into molecules by green leaves
D. incorporation of H_2O from the soil into molecules by green leaves
E. absorption of solar radiation into the leaf

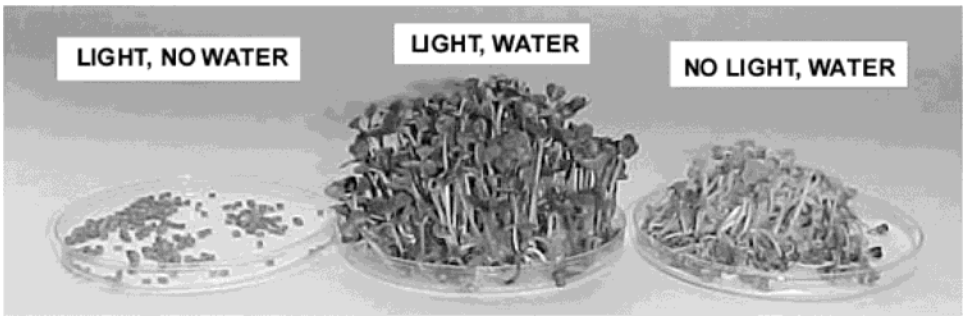
[Essay prompt: Explain this huge increase in mass.]



6. Seed corn
Each spring, farmers plant about 5-10 kg of seed corn per acre for commercial corn production. By the fall, this same acre of corn will yield approximately 4-5 metric tons of harvested corn. Which of the following processes contributes the most to this huge increase in biomass?



7. Radish seeds in light (Ebert-May *et al.*, 2003)



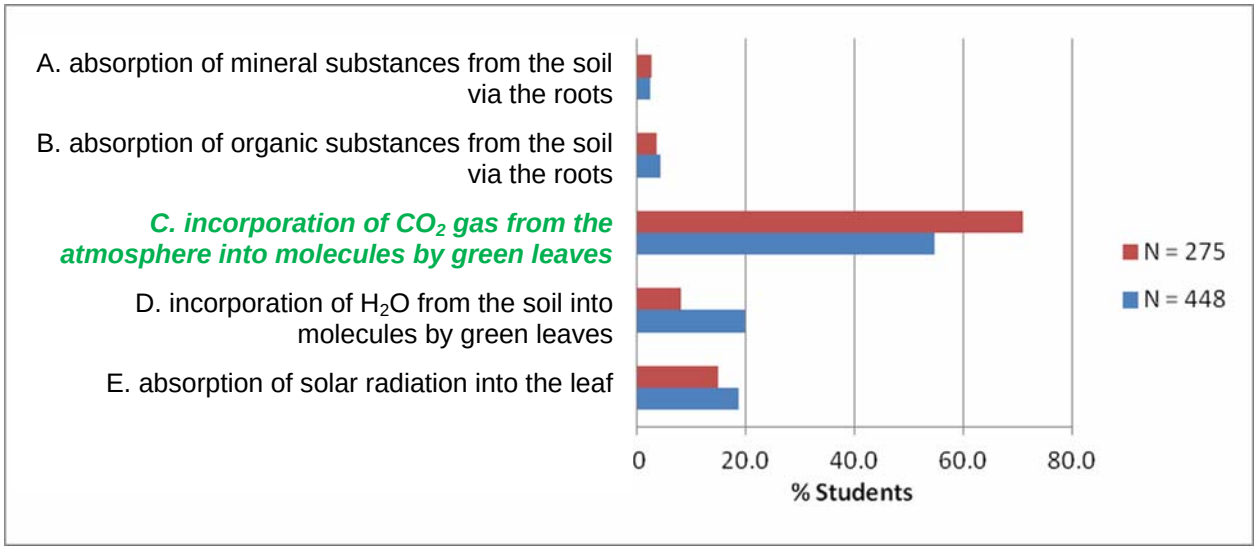
Results: 1.48g 3.28g 1.17g

The following question is based on this experiment: Three batches of radish seeds, each with a starting weight of 1.5g (dry), were placed in petri dishes and provided only with light or water or both, as shown in the photo. After 1 week, the material in each dish was dried and weighed. The results are shown below each petri dish.

Which of the following processes contributed the most to the increased biomass of the "Light, Water" treatment?

A. absorption of mineral substances from the soil via the roots
B. absorption of organic substances from the soil via the roots
C. incorporation of CO_2 gas from the atmosphere into molecules by green leaves
D. incorporation of H_2O from the soil into molecules by green leaves
E. absorption of solar radiation into the leaf

[Essay prompt: Explain which process contributes the most to the increased biomass of the "Light, Water" treatment.]



Mass loss in plants

8. Radish seed in the dark

Where did the mass go that was lost by the seedlings in the "No light, Water" treatment?

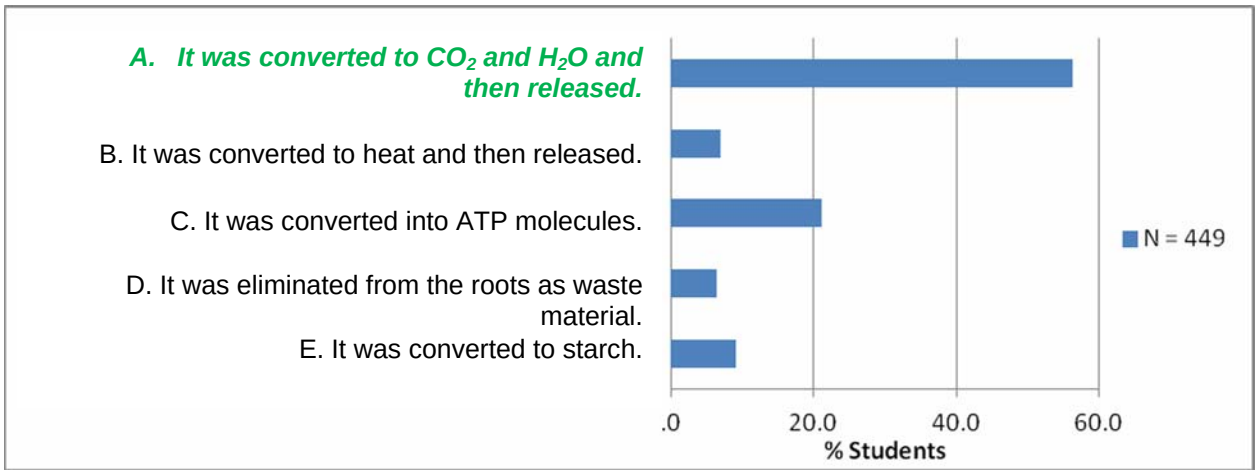
A. It was converted to CO_2 and H_2O and then released.

B. It was converted to heat and then released.

C. It was converted into ATP molecules.

D. It was eliminated from the roots as waste material.

E. It was converted to starch.



9. Geranium in the dark

A potted geranium plant sits in a windowsill, absorbing sunlight. After I put this plant in a dark closet for a few days (but keeping it watered as needed), will it weigh more or less (discounting the weight of the water) than before I put it in the closet?

A. It will weigh less because it is still respiring.

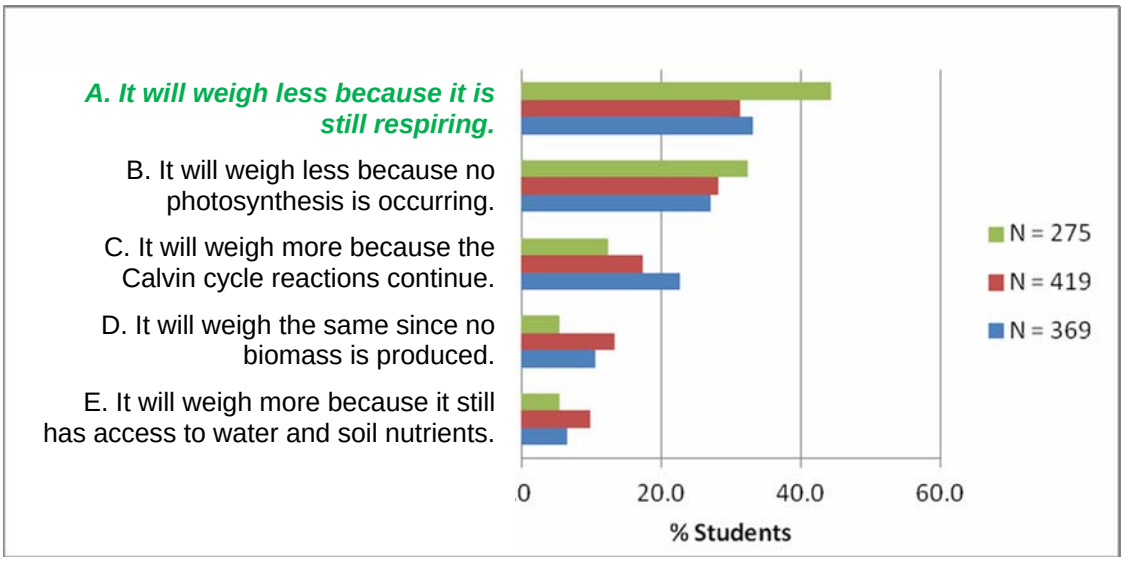
B. It will weigh less because no photosynthesis is occurring.

C. It will weigh more because the Calvin cycle reactions continue.

D. It will weigh the same since no biomass is produced.

E. It will weigh more because it still has access to water and soil nutrients.

[Essay prompt: Will it weigh more or less (discounting the weight of the water) than before I put it in the closet? Explain your answer.]



Tracing energy

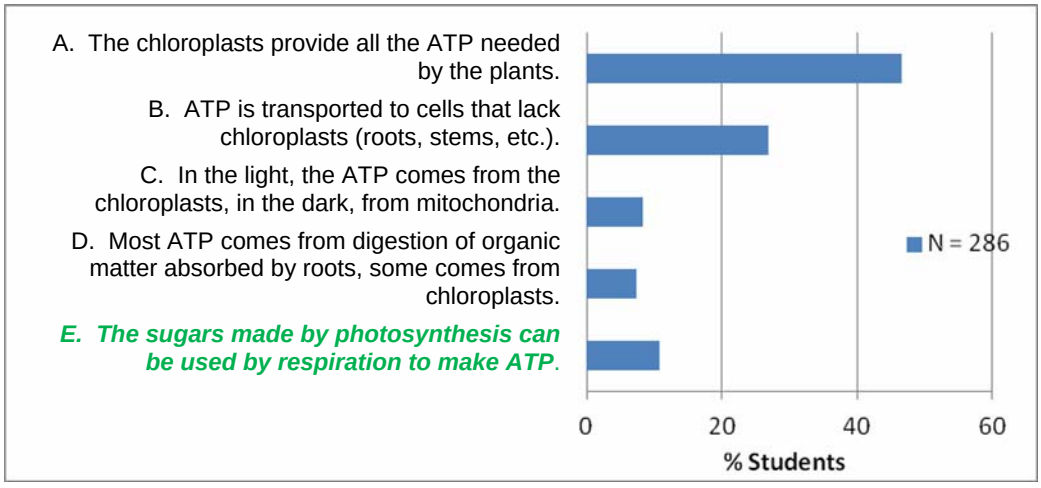
The relationship between photosynthesis and respiration

10. Energy sources for plants

Which of the following best describes how a plant cell gets the energy it needs for cellular processes?

A. The chloroplasts provide all the ATP needed by the plants.
B. ATP is transported to cells that lack chloroplasts (roots, stems, etc.).
C. In the light, the ATP comes from the chloroplasts, in the dark, from mitochondria.
D. Most ATP comes from digestion of organic matter absorbed by roots, some comes from chloroplasts.
E. The sugars made by photosynthesis can be used by respiration to make ATP.

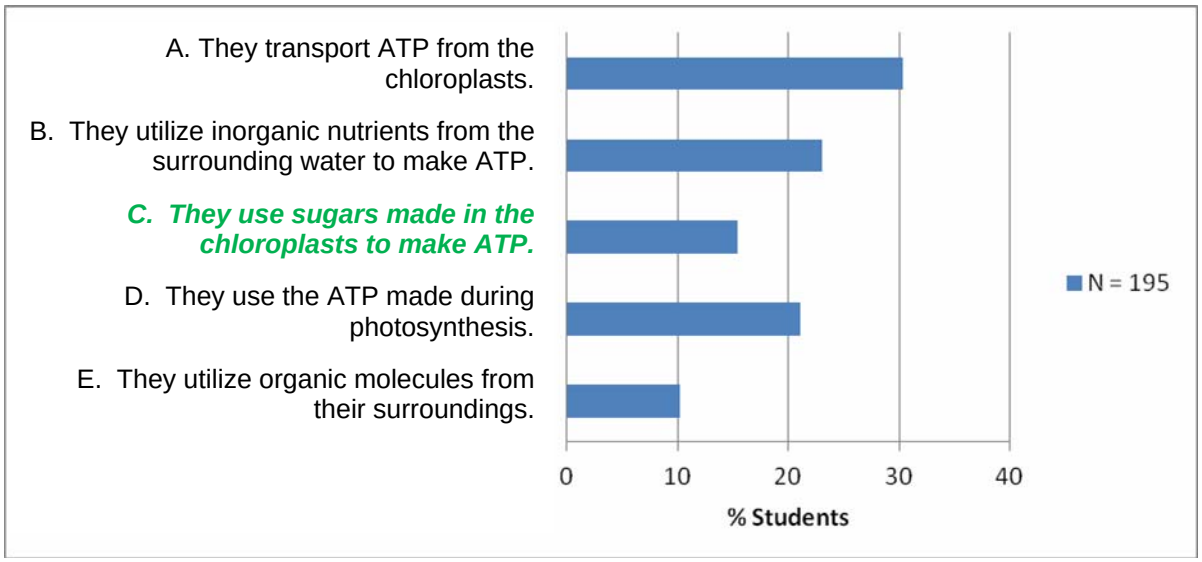
[Essay prompt: Explain how a plant cell gets the ATP it needs for cellular processes.]



11. *Euglena*

Euglena are single-celled, photosynthetic eukaryotes. How do *Euglena* obtain energy to do such cellular work such as active transport across membranes?

A. They transport ATP from the chloroplasts.
B. They utilize inorganic nutrients from the surrounding water to make ATP.
C. They use sugars made in the chloroplasts to make ATP.
D. They use the ATP made during photosynthesis.
E. They utilize organic molecules from their surroundings.



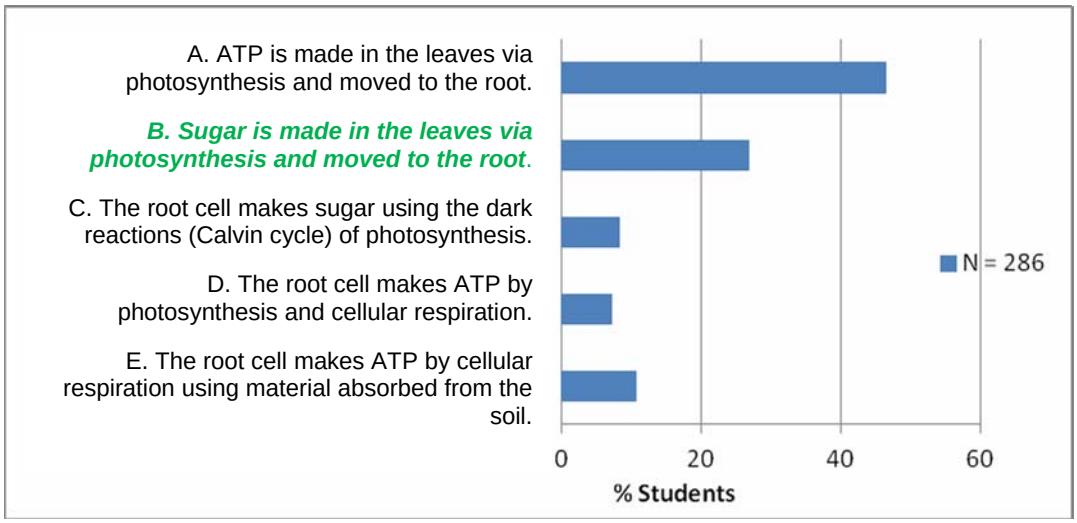
Tracing energy and identifying scale and location

Energy sources for plants

12. Geranium root cells

A potted geranium sits in a windowsill absorbing sunlight. How does a root cell (which is not exposed to light) obtain energy to do cellular work such as active transport across its membrane?

A. ATP is made in the leaves via photosynthesis and moved to the root.
B. Sugar is made in the leaves via photosynthesis and moved to the root.
C. The root cell makes sugar using the dark reactions (Calvin cycle) of photosynthesis.
D. The root cell makes ATP by photosynthesis and cellular respiration.
E. The root cell makes ATP by cellular respiration using material absorbed from the soil.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B. Sugar is made in the leaves via photosynthesis and moved to the root.
C. The root cell makes sugar using the dark reactions (Calvin cycle) of photosynthesis.
D. The root cell makes ATP by photosynthesis and cellular respiration.
E. The root cell makes ATP by cellular respiration using material absorbed from the soil.
N = 286
0
20
40
60
% Students

Appendix B. Framework

	Tracing Matter	Tracing Energy	Context / Location
ECOSYSTEM LEVEL			
Transformation of biomass and energy through food webs	Autotrophs produce reduced carbon compounds from CO_2 and water as energy sources and building materials. The reduced carbon compounds are passed along food webs as one organism consumes another. When the reduced carbon compounds are used as energy sources CO_2 is often released.	Most autotrophs convert sunlight to chemical potential energy in reduced carbon compounds. The reduced carbon compounds are used as energy sources and building materials by all organisms.	
ORGANISMAL LEVEL (Multi-cellular organisms)			
Converting Light Energy (Sun) into Chemical Energy (Food)	Carbon dioxide and water from the environment provide the building blocks for the synthesis of organic compounds. The initial products of photosynthesis are sugars which can be made into other molecules with the addition of N, P, and S as needed. Oxygen and water leave the organism.	Photosynthetic organisms transform the light energy from the sun into chemical potential energy stored in the bonds of carbohydrates.	Carbohydrates are made in cells with photosynthetic pigments. Sugars and other monomers are transported throughout the body. Polymers are made in cells as needed from monomers with addition of other elements, N,P, and S.
CELLULAR LEVEL (C)			
Photosynthesis			

	$6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$	Light energy (photons) $\rightarrow$ Chemical potential energy (CPE) in the C-C and C-H bonds in reduced carbon compounds (sugar $(CH_2O)_n$).	Occurs entirely within in the chloroplasts of the cell. Requires specialized membranes and pigment.
SUB-CELLULAR LEVEL (SC)			
Light-Dependent Reactions I	$12H_2O + 12ADP + 12P_i + 12NADP^+ \rightarrow 6O_2 + 12ATP + 12NADPH + 12H^+$	Light energy (photons) $\rightarrow$ CPE in proton gradient CPE in ATP Light energy (photons) $\rightarrow$ CPE in NADPH	Occurs in membranes (thylakoid membranes) facing the inside of the chloroplast's grana.
Calvin Cycle (Light-Independent Reactions)	$3CO_2 + 9ATP + 6NADPH + 6H^+ \rightarrow$ (*3-carbon sugar phosphate*) $C_3H_5O_3P_i + 3H_2O + 9ADP + 8\ P_i + 6NADP^+$	CPE in bonds of ATP & NADPH $\rightarrow$ CPE in the C-C and C-H bonds in reduced carbon compounds (3-carbon sugars such as glyceraldehyde phosphate)	Occurs in the stroma (fluid portion) of the chloroplasts.
Hexose & Other Macromolecule Production (Light-Independent Reactions)	*(3-carbon sugar phosphates)* $2C_3H_5O_3P_i \rightarrow$ *(6-carbon sugar phosphate)* $C_6H_{11}O_6P_i + P_i$ **3- & 6-carbon sugars** made into other **building blocks** with addition of **N, S, and P** as needed	CPE in stored in the C-C and C-H bonds in carbohydrates and other molecules. Much synthesis of macromolecules is coupled to the use of ATP.	Occurs in the cytosol

Atoms in equations are shown in color as an aid to tracing the fate of particular atoms.