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A Computer-Assisted Personalized Approach in an Undergraduate Plant Physiology Class[1]

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We used Computer-Assisted Personalized Approach (CAPA), a networked teaching and learning tool that generates computer individualized homework problem sets, in our large-enrollment introductory plant physiology course. We saw significant improvement in student examination performance with regular homework assignments, with CAPA being an effective and efficient substitute for hand-graded homework. Using CAPA, each student received a printed set of similar but individualized problems of a conceptual (qualitative) and/or quantitative nature with quality graphics. Because each set of problems is unique, students were encouraged to work together to clarify concepts but were required to do their own work for credit. Students could enter answers multiple times without penalty, and they were able to obtain immediate feedback and hints until the due date. These features increased student time on task, allowing higher course standards and student achievement in a diverse student population. CAPA handles routine tasks such as grading, recording, summarizing, and posting grades. In anonymous surveys, students indicated an overwhelming preference for homework in CAPA format, citing several features such as immediate feedback, multiple tries, and on-line accessibility as reasons for their preference. We wrote and used more than 170 problems on 17 topics in introductory plant physiology, cataloging them in a computer library for general access. Representative problems are compared and discussed.

Information technology is increasingly used in a variety of ways to aid instruction in the biological sciences. Laboratories or lectures may include computerized simulations of life processes (Jaffe and Lynch, 1989; Hutchings et al., 1994; Hall, 1996; Beneski and Waber, 1997), many tutorials have been written (Blakely, 1988; Dewhurst et al., 1989; van Geloven, 1994), some publishing companies now offer CD-ROM study guides to accompany their textbooks, and many instructors use a World Wide Web site to supplement their courses because the Web is a vast and rapidly growing source of information (Somerville et al., 1997).

Information technology is rarely used for homework sets in the biological sciences, however. Regular assigned homework is recognized as a valuable tool in classes in the physical sciences: it is an active rather than a passive form of learning, it challenges students to keep up with material, and it encourages students to consult on an individual basis with the instructors. In the physical sciences, several computer programs have been developed to create individualized problem sets in which random numbers are used to generate unique data for each student (Castleberry and Lagowski, 1970; Kashy et al., 1993; Spain, 1996; Hodges, 1994). It is difficult to imagine a class in mathematics or physics that lacks regular homework; few would argue that calculus can be mastered without practice in solving problems. Biology, by contrast, seems a more qualitative subject in which much of the material taught is conceptual rather than numerical. Thus, some biology instructors may regard homework as unnecessary or even inappropriate for the teaching of conceptual material. In addition, many instructors are reluctant to give regular homework because of the time required to grade it, or even because it is difficult to control the possibility of students copying each others' answers.

We believe that homework is as valuable a teaching and learning tool in the biological sciences as it is in the physical sciences. Ideal homework assignments should be individualized (similar in form but different in detail) so that students can be encouraged to work together to discuss concepts but to do their own work to arrive at correct answers to their particular problems. Cooperative learning has been used in college physics, astronomy, chemistry, biology, earth science, and business classrooms to improve learning (Mazur, 1997). Some desirable learning outcomes thus promoted include higher achievement, increased retention, more frequent and higher-level reasoning, critical thinking, more time on task, and improved attitudes toward teachers (Johnson et al., 1991). A cooperative-learning environment develops when students study together to solve similar but nonidentical problems. Individualized homework also encourages each student to self-organize and reorganize knowledge; in the words of Pines and West (1986): "Knowledge is not acquired passively."

We adapted the CAPA software system to develop individualized, networked problem sets for our large-enrollment, junior-level plant physiology course at MSU. The CAPA system, originally developed for physics classes at MSU (Kashy et al., 1993, 1995), is now in use for chem-

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Abbreviations: BSCS, Biology Study Center Software; CAPA, Computer-Assisted Personalized Approach.

istry and physics courses at several universities around the country (see http://www.pa.msu.edu/educ/CAPA/). CAPA generates a wide variety of quantitative and qualitative problems. The problems within each homework assignment take on the same form and cover the same principles for all students, but they are unique for each student. Each student receives a printed assignment with quality graphics. They also can access their assignments and submit answers on line, receiving immediate feedback. If the answer is correct, the computer immediately rewards the student; if it is incorrect, the student may resubmit an answer without penalty until either a predefined limit on the number of tries is reached or the due date and time for the problem set is reached. Hints for many problems are available on line, and after the due date, on-line explanations are also available, if provided by the instructor. While they are on line, students may view earlier assignments or a summary of their scores to date. CAPA keeps track of the number of tries made by each student on each problem, thus allowing the instructor to identify difficult and/or poorly constructed problems and address these in subsequent lectures. In another file, CAPA records the times, durations, and locations of student log-ins. CAPA's Grader program generates a summary of scores for each student, which frees the instruction staff to arrange individual interactions with students and to give weekly homework assignments in a large-enrollment course.

In this paper, we describe the types of plant physiology homework problems we have created with CAPA, present the results of surveys of students' responses to and acceptance of CAPA in our plant physiology course, and present a comparison of student performance on examinations between current students (with CAPA) and students from previous years (without CAPA), highlighting the positive effects of regular homework assignments.

MATERIALS AND METHODS

CAPA was originally developed at MSU (Kashy et al., 1993). The CAPA software operates on any UNIX server connected to the campus ethernet system. The main CAPA host can be accessed from either a PC or a Mac running X-Server software. We used the Windows-NT (Microsoft, Redmond, WA) operating system and eXceed (Hummingbird Communications, Ltd., North York, Ontario, Canada) X-server software. CAPA software consists of four main modules (three have been described by Kashy et al. [1993]) designed to create and preview problem sets, parse and print sets, handle remote sessions by students who access CAPA, and generate grade reports for the class or for individual students. Assignments are prepared by making a prototype source file with the Quizzer program. Templates are available for most problem types. The qualitative problems contain multiple parts, so for each of these parts, up to four variants are written that are randomly selected and permuted by Quizzer for individual assignments. Random numbers within a defined range are used to generate data for quantitative problems. Students connect to the host computer via the Internet and access assignments or grade summaries by entering the course acronym, their student number, and the unique CAPA identification number assigned by CAPA to that student's assignment. This process secures access to individualized assignments.

Student Enrollment and Survey of Student Evaluations of CAPA in Plant Physiology

Most students enrolled in this course were nonmajors, although majors can enroll in it as the first course in the field. A typical student curriculum distribution (for Spring 1997) included a majority of students (69%) in various agricultural programs (typically crop and soil science, forestry, or horticulture), 17% in other sciences (biology for secondary science teachers, biology, or zoology), and only 9% botany majors. Nearly all students took the course to satisfy a program requirement.

At the end of each semester, an anonymous survey was distributed to each student to evaluate their acceptance and opinions about the plant physiology sets we constructed with CAPA. The nature of problems in plant physiology and physics (for which CAPA was originally designed) are sufficiently different that we decided to assess student attitudes toward both the system and our homework assignments. The frequency of each response and the Pearson correlation coefficients (item intercorrelations) were determined by the scoring office in the Department of Computer Sciences at MSU.

Statistics

Mean examination scores for the last 3 years were analyzed for statistically significant differences by applying Student's t test when conditions for normality and equal variance were met or otherwise with the Mann-Whitney rank-sum test. The same instructor (K.D.N.) taught the course for the semesters analyzed.

RESULTS AND DISCUSSION

CAPA Homework Assignments in Plant Physiology

Many different types of problems, both quantitative and qualitative, can be written with CAPA. In Figure 1, selected plant physiology problems representing a variety of types are presented as a sampler CAPA homework set for two fictitious students (the authors). By comparing the two sets, the reader can see how items within each problem are randomized. The types of problems are described below, and corresponding example problem(s) in Figure 1 are indicated in parentheses. The correct answers are given in "Appendix."

Selecting All Correct Statements or Answers (problem 1): In this type of problem, several statements (or "items"; there are seven [A–G] in this example) are listed and the student must select all of the correct statements. For any student, from one to all of the statements listed may be correct; or there may be only one correct selection for one student and seven for another. For each item listed, there are up to four possible variants. For each student, CAPA randomly selects one variant of each item and then per-

A

Artus, Nancy N **Section 4**

Bot 301 *Set 20*

SAMPLE – MSU – 1998. Due Tue, Dec 1, 1998 at 18:00
CAPA ID is 9593

1. [1pt] α-Ketoglutarate + CoA + NAD^+ $\rightarrow$ Succinyl-CoA + NADH + CO_2
Give ALL correct answers pertaining to this equation (i.e., B, AC, BCD...).

A) This is an enzyme-catalyzed reaction.
B) The organic acid on the left in this reaction becomes oxidized.
C) The number of carbons in the substrate organic acid is one less than the number in the product organic acid (if 'CoA' is not considered).
D) This is a decarboxylation reaction.
E) NAD^+ is the electron acceptor.
F) Some energy of the substrate organic acid is conserved as reducing equivalents.
G) This reaction occurs in glycolysis.

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2. [1pt] Scarlet Pimpernel is a long-day plant with a critical daylength for flowering of 12 hours. Indicate whether you expect scarlet pimpernel plants to remain vegetative or to flower on each of the following photoperiods. (h=hours; L=light; D=dark; R=red; FR=far-red. For each statement select V:Vegetative, F:Floral If A and B are F and the rest V, enter FFVVVV).

A) 8 h L, 16 h D; D interupted mid-way by R L
B) 10 h L, 14 h D; D interupted mid-way by R-FR L
C) 14 h L, 10 h D
D) 4 h L, 8 h D
E) 7 h L, 0.5 h D, 6.5 h L, 10 h D
F) 9 h L, 15 h D

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3. [1pt] Match each important plant compound (often polymer) listed at the left with the *most appropriate* building block (or monomer) listed at the right. (If the first corresponds to B, and the next 4 to C, enter BCCCC)

1) carotenes	A. nucleotides
2) DNA	B. L-amino acids
3) rubber	C. pyrrole rings
4) chlorophyll a 'head' group	D. isoprenoid unit
5) polypeptides	

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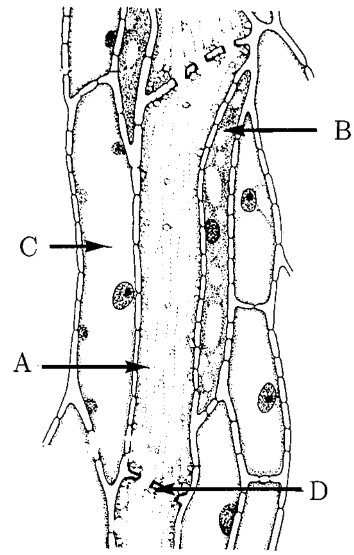
4. [1pt] The diagram represents a longitudinal section of some phloem tissue. For each description below, select (in order) the symbol in the picture.



1) sieve-tube member (or sieve element)
2) phloem parenchyma cell
3) companion cell
4) a cell whose probable function is to carry out the metabolic functions lost in the 'other' cell type
5) a cell in which mass transport occurs
6) a cell that does not respire
7) sieve plate
8) a living cell devoid of most organelles

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5. [1pt] List the following stages of seed germination in the order that they occur. (If B occurs first, then A, C, F, E and D occurs last, enter BACFED)

A) mobilization of food reserves
B) imbibition (water uptake)
C) radicle emergence
D) release of hydrolytic enzymes
E) increase in respiration
F) shoot elongation

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6. [1pt] An algal cell with $\Psi\pi$=-11 bars is living in a pond with $\Psi\pi$=-2 bars. What is the Ψp of the algal cell assuming it is in equilibrium with its environment? If you had microscopic fingers and could gently squeeze this alga, would it feel limp or firm? For your answer, first enter the numerical value for Ψp without units, follow it by a comma, and then enter L for Limp or F for Firm.

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Figure 1. Two versions of a sample set of selected CAPA homework problems in plant physiology. (Figure continues on next page.)

Nadler, Kenneth D **Section 4**

B

Bot 301 *Set 20*

SAMPLE - MSU - 1998. Due Tue, Dec 1, 1998 at 18:00
CAPA ID is 8422

1. [1pt] Pyruvate + CoA + NAD^+ → Acetyl-CoA + NADH + CO_2
Give ALL correct answers pertaining to this equation (i.e., B, AC, BCD...).

A) NAD^+ becomes reduced.
B) The number of carbons in the substrate organic acid is one less than the number in the product organic acid (if 'CoA' is not considered).
C) This is a decarboxylation reaction.
D) A product of this reaction feeds into the TCA cycle.
E) Some energy of the substrate organic acid is conserved as reducing equivalents.
F) The organic acid on the left in this reaction becomes reduced.
G) This is an oxidation-reduction reaction.

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2. [1pt] Poinsettia is a short-day plant with a critical daylength of 12.25 h. Indicate whether you expect poinsettia plants to remain vegetative or to flower on each of the following photoperiods. (h=hours; L=light; D=dark; R=red; FR=far-red. For each statement select V:Vegetative, F:Floral If A and B are F and the rest V, enter FFVVVV).

A) 14 h L, 10 h D
B) 4 h L, 8 h D
C) 8 h L, 16 h D; D interupted every 4 h by R-FR L
D) 8 h L, 0.5 h D, 7.5 h L, 8 h D
E) 6 h L, 18 h D; D interupted every 6 h by R L
F) 8 h L, 16 h D

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3. [1pt] Match each important plant compound (often polymer) listed at the left with the *most appropriate* building block (or monomer) listed at the right. (If the first corresponds to B, and the next 4 to C, enter BCCCC)

1) chlorophyll a 'head' group	A. nucleotides
2) RNA	B. isoprenoid unit
3) proteins	C. pyrrole rings
4) phytosterols	D. L-amino acids
5) xanthophylls	

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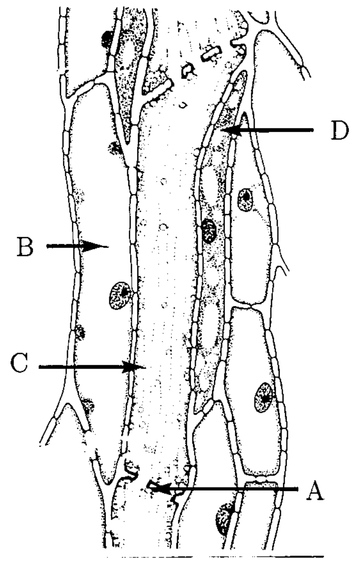
4. [1pt] The diagram represents a longitudinal section of some phloem tissue. For each description below, select (in order) the symbol in the picture.



1) phloem parenchyma cell
2) companion cell
3) a living cell devoid of most organelles
4) a cell that does not respire
5) a cell in which mass transport occurs
6) sieve-tube member (or sieve element)
7) a cell whose probable function is to carry out the metabolic functions lost in the 'other' cell type
8) sieve plate

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5. [1pt] List the following stages of seed germination in the order that they occur. (If B occurs first, then A, C, F, E and D occurs last, enter BACFED)

A) mobilization of food reserves
B) shoot elongation
C) increase in respiration
D) radicle emergence
E) release of hydrolytic enzymes
F) imbibition (water uptake)

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6. [1pt] An algal cell with $\Psi\pi$=-10 bars is living in a pond with $\Psi\pi$=-1 bars. What is the Ψp of the algal cell assuming it is in equilibrium with its environment? If you had microscopic fingers and could gently squeeze this alga, would it feel limp or firm? For your answer, first enter the numerical value for Ψp without units, follow it by a comma, and then enter L for Limp or F for Firm.

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Figure 1. (Figure is continued from previous page).

mutes the order of the items. Thus, with seven items and four variants of each item, as in problem 1, we can generate $4^7 \times 7$ factorial, or approximately 86 million, unique versions of this particular problem. In addition, the "choose" function was used in the text of problem 1 to randomly select one of three equations from respiration (the oxidative decarboxylation of pyruvate, isocitrate, or α-ketoglutarate), which further increases the variation between problems.

Selecting Answers in Sequence (problem 2): A correct answer for this type and the following three types of problems is a sequence of entries, the number of which corresponds to the number of items (six entries for problem 2). The choices for entries may be A/B, true/false, greater than/less than/equal to, or any set of answer variants defined by the instructor. For example, in problem 2 the student selects between F for floral and V for vegetative; a correct answer would take the form FFFVVF. Again, the choose function was used in the text of problem 2 so that each student is randomly assigned any one of several problems on long-day or short-day flowering plants, together with the appropriate critical day length.

Matching (problem 3): The student matches each item (1–5) to each property (A–D). There are up to four variants for each item, but the properties are the same for each student. Matching does not need to be one-to-one, because the properties may be used more than once or not at all.

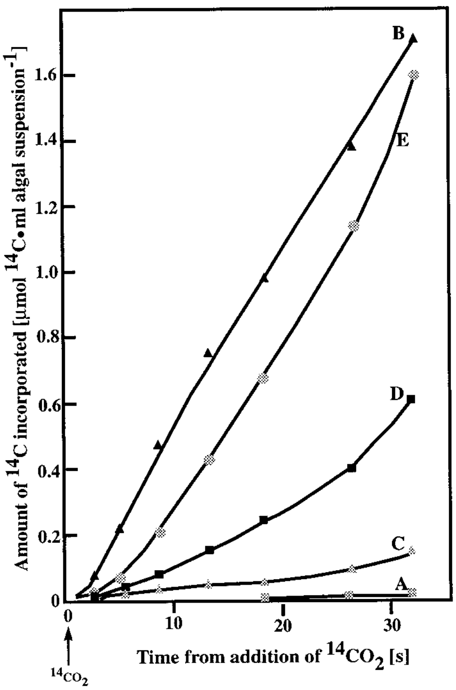
Matching to Labels in a Figure (problem 4): CAPA randomizes the labels (A–D) on a figure and permutes the order of the items (1–8). The author of the problem may choose to draw the figure with a graphics program or scan an existing figure.

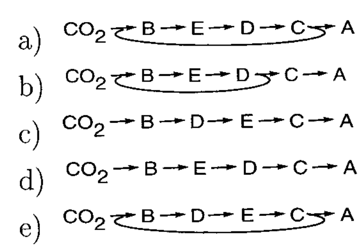
Ranking (problem 5): The student must list the items in the appropriate order. The ranking may be in time (as in this example), magnitude, or order in a biosynthetic pathway.

Free Form (problem 6): There is no template for writing this type of problem as there is for the other problems. Problems requiring a calculation are often written in free form. Random numbers within limits defined by the instructor may be used to produce a unique problem for each student.

The problems in the sample sets (Figs. 1 and 2) test several levels of knowing or categories of the cognitive domain (Bloom et al., 1956). The first and fifth problems in set one (Fig. 1) test for a base level of cognition ("knowledge"): The student names, defines, identifies, or orders information. The third, fourth, and sixth problems require a higher order of understanding (the third or "application" level): The student relates a precursor or monomer as a

1. [1pt] The curves below show the short term labeling of photosynthetic intermediates (A through E) with ^{14}C-containing carbon dioxide during photosynthesis. Select ALL of the following metabolic pathways (a to e below) which are consistent with the kinetics of the labelling of these intermediates (e.g., enter b, bc, ade, abde etc.).





2. [1pt] Referring to the problem and problem statements above: After several minutes of exposure to ^{14}C-carbon dioxide, all intermediates (A through E) reach constant radioactivity. The figure below illustrates what occurs when we shift from high to low levels of carbon dioxide input. (At 0.003% CO_2, CO_2 is in short supply.) From the correct choices in problem 1, select those metabolic pathways (a to e above) which are consistent with the data shown in both figures.

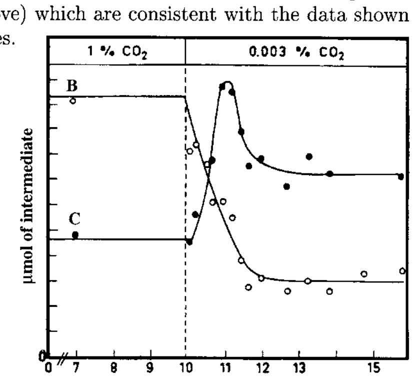


Figure 2. Two sample problems on $^{14}CO_2$ fixation in photosynthesis. The hint for the first problem states, "^{14}C is an isotope of carbon that allows tracking of carbon. The compounds that are detected with ^{14}C label after feeding $^{14}CO_2$ are those that are made in the CO_2 assimilation pathway. The order that they appear in is the order that they occur in the pathway." The hint for the second problem states, "Consider the reaction X + Y → Z. If Y is in short supply, X will accumulate and the level of Z will diminish." The figures are redrawn with permission (Mohr and Schopfer, 1995).

Table I. *Subject areas of CAPA plant physiology problems and numbers of problems written*

Subjects	Problems Written as of October 1998
	no.
1. The cell (organelles and membranes)	8
2. Basic life functions: Comparison of mammals and plants	9
3. Water relations: Diffusion, bulk flow, osmosis, and water potential and its components	26
4. Transpiration, guard-cell function	13
5. Mineral nutrition	10
6. Membrane transport	6
7. Phloem translocation	5
8. Plant composition: Macromolecules and precursors	8
9. Enzymes: Activity, definition, and mechanisms	8
10. Respiration: Glycolysis, TCA cycle, electron transport rates, and respiratory quotient	9
11. Photosynthetic CO_2 fixation	5
12. Light reactions of photosynthesis: Pigments, spectra, Z scheme, electron transport	8
13. Nitrogen and sulfur metabolism	10
14. Development	8
15. Plant hormones	8
16. Photomorphogenesis	8
17. Plant genetics	21

building block to various products, relates an element of a phloem-tissue diagram to structure and function, or computes a cell pressure potential, hence turgidity of the cell. The second problem in set one demands that the student analyze the photoregime and determine the relationship between photoperiod and the critical photoperiod, predicting flowering outcome; this represents the fourth ("analytical") level of knowing. The problems in sample set two require the highest order of understanding ("evaluation"): The student hypothesizes (level five or "synthesis") an order of intermediates in the carbon dioxide fixation pathway based on labeling kinetics and then evaluates which subset of the pathways proposed as answers would result in those kinetic data. More than one of the answers is correct. The data in problem 2 in set two are necessary to evaluate which of several possible pathways is correct; this tests understanding at the evaluation level.

Because a variety of qualitative questions can be written with CAPA (Kashy et al., 1995), it is readily adaptable to the biological sciences. We have written more than 170 problems for our third-year, university-level course (Botany 301) covering 17 areas in plant physiology (Table I). In all of these subject areas, most or all of the problems we wrote are qualitative in nature. Quantitative problems were written for the areas of plant water relations, transpiration, enzyme kinetics, and Mendelian genetics. Our problems have been cataloged in a computer library and are available for use at other institutions that adopt CAPA (see http://www.pa.msu.edu/educ/CAPA/ for CAPA overview, institutions with CAPA licenses, and extensive contact, system requirement, and licensing information, documentation, and a sample set).

There are several features of CAPA (immediate feedback, multiple tries, and the hints) that, when combined with a well-planned lecture, can be used successfully with challenging problems. The problems presented in Figure 2 require the student to develop the pathway for photosynthetic carbon fixation from Calvin and Benson's original data. The hints available for these problems (see legend to Fig. 2) guide students by describing the logic required to solve the problems. When these problems were used in the Spring 1997 semester, 69 of 76 students (91%) who at-

Table II. *The CAPA survey to evaluate student responses to CAPA homework in plant physiology and student responses*

Survey questions	Fall 1996			Spring 1997		
	No	Yes	*n*	No	Yes	*n*
		%			%	
1. Have you had CAPA homework sets in other classes?	29	71	55	50	50	66
2. Were those positive learning experiences?	26	74	42	44	56	39
3. CAPA produces an individualized homework set for you. Did this encourage you to discuss answers with your classmates?	42	59	53	25	75	68
4. CAPA is available on line in contrast to traditional assignments available only in hard copy. Was this feature helpful in learning?	16	84	55	32	68	69
5. Was the immediate-feedback feature of CAPA on-line sets helpful in learning?	18	82	55	19	82	69
6. CAPA allows multiple tries without penalty at solving each problem. Did this help your grade on the problem set?	2	98	55	9	91	69
7. Did the multiple-try feature help you learn?	–[a]	–	–	28	73	69
8. Did you use the hints?	–	–	–	22	79	65
9. Were the hints helpful in learning?	27	73	55	52	48	58
10. Did you look at the explanations posted after the due date?	86	15	55	54	46	67
11. If so, did the explanations help you learn?	–	–	–	31	69	36
12. Did you find it rewarding to have CAPA tell you when you were correct?	6	95	55	17	83	69
13. If you needed more than one try to answer all of the problems correctly, did you try to solve them again?	2	98	55	12	87	68

[a] –, Not available in the Fall 1996 semester.

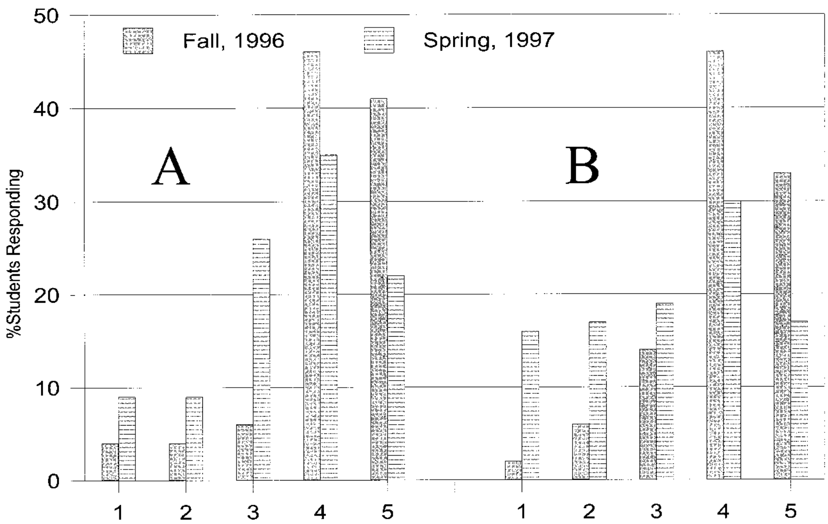


Figure 3. Student responses from two semesters to survey questions 14 and 15 on CAPA. A, Question 14 is, "As a learning tool, I found CAPA . . . . " B, Question 15 is, "Rate your experience with CAPA." Response choices available are (1) quite negative, (2) somewhat negative, (3) indifferent, (4) somewhat helpful, and (5) quite helpful. The percentage of the responding students in each semester selecting each choice is shown.

tempted these problems answered both correctly. We set the limit to answer each question correctly at 10 tries. The average number of tries to solve problem 1 was 2.0 ± 1.8, and 44 students (58%) answered it correctly on the first try. The average number of tries to solve problem 2 was 2.3 ± 1.8, and 37 students (49%) answered it correctly on the first try. Thus, the students did very well on a set of challenging problems that we had been reluctant to include in previous traditional homework sets.

Student Assessment of CAPA in Plant Physiology

Students indicated in anonymous surveys that they prefer homework assignments in the CAPA format to traditional hand-graded sets. The anonymous survey form of CAPA assignments in Botany 301 and the students' responses are presented in Table II and Figures 3 and 4. Fifty-five of 56 students (98%) completed the survey in the Fall 1996 semester, when the course was taught by other colleagues, and 69 of 84 students (72%) completed the survey in the Spring 1997 semester when one of us (K.D.N.) taught the course. The overall response to our CAPA assignments was positive (survey questions 14–16, Figs. 3 and 4). The majority of plant physiology students responding (80% and 69% in Fall and Spring, respectively) indicated that they favor CAPA homework over hand-graded homework (question 16), with only 4% each semester indicating that they strongly favor hand-graded homework. The particular features identified by students as being the most helpful were the multiple tries without penalty (question 6) and the immediate feedback (question 5). Ninety-eight percent (Fall 1996) and 91% (Spring 1997) of students responding considered the multiple tries feature to be helpful, and 98% and 87% said that they tried to solve problems more than once (question 13). This feature encouraged students at all levels to keep trying until they had answered every problem correctly. Eighty-two percent of students each semester indicated that receiving immediate feedback helped them learn, and 95% (Fall 1996) and 83% (Spring 1997) found it rewarding when CAPA told them that their answers were correct (question 12). When weekly CAPA assignments were given, 75% of students (Spring 1997) said that having individualized homework sets encouraged them to discuss homework with classmates (question 3). The differences among students who reported previous experiences with CAPA (Table II, questions 1 and 2) between Fall 1996 and Spring 1997 probably reflect their individual histories in specific MSU physics and chemistry courses, because only some courses and course sections use CAPA. Students still remained positive about some of their experiences with CAPA in the Spring 1997 plant physiology course compared with students in the Fall 1996 course (Figs. 3 and 4). We attribute these affective differences to the increased frequency (and thus decreased novelty) of CAPA assignments and their impact on final grades during the Spring 1997 semester.

Many students reported anecdotally that they devote several hours to each CAPA homework set. Our log-in data

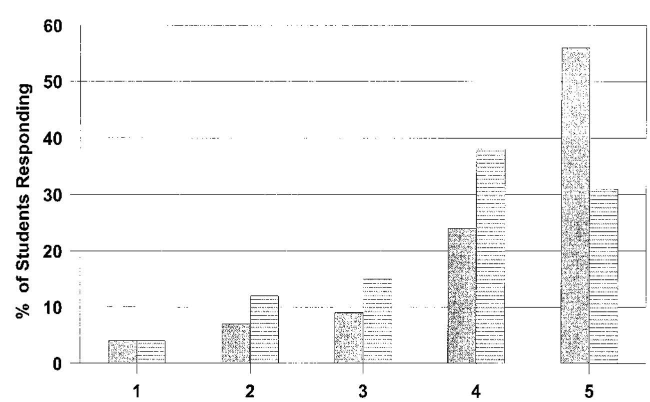


Figure 4. Student responses from two semesters (gray bars, Fall 1996; striped bars, Spring 1997) to survey question 16, "If I had a choice between CAPA assignments used in BOT 301 [Botany 301] and hand-graded essay homework, I would be . . . . . ." Response choices available are (1) strongly in favor of hand-graded homework, (2) moderately in favor of hand-graded homework, (3) indifferent, (4) moderately in favor of CAPA, and (5) strongly in favor of CAPA. The percentage of responding students selecting each choice is shown.

(not shown) suggest that the students make multiple attempts on most problems, indicating increased time on task. We also observed a generally improved student attitude toward the instructors and an increase (1 order of magnitude) in the number of students seeking the instructor's assistance in answering CAPA homework problems compared with typical homework sets. These effects were observed previously in physics courses using CAPA (Kashy et al., 1993). We believe that there are three major reasons for the increased student time on CAPA homework: Students know that they have the opportunity to rework answers multiple times, they are not penalized for incorrect answers, and they are not judged while they are learning. An important element of learning is making mistakes and then correcting them. By eliminating ranking during the learning process, CAPA is eliminating a discouraging learning environment for many students.

The student responses were analyzed for correlations between answers to the survey questions. For example, if a student answered yes to question 1, was the probability greater than 95% that he or she would answer yes to question 5? Students rating CAPA as a helpful learning tool (question 14) were likely to consider the on-line and "multiple-try" features of CAPA helpful, and they felt rewarded when the computer told them that they were correct. Students who had a positive experience with CAPA (question 15) liked these same features as well as the immediate feedback and the explanations that are available on line after the due date. Students who used CAPA in a previous course (question 1) were likely to prefer CAPA homework over hand-graded homework. (The converses are also true: The small subset of students who thought CAPA was not a useful tool did not find the on-line and multiple-try features useful, etc.) The only significant negative correlation occurred between questions 3 and 10, suggesting that students who worked individually rather than in groups were more likely to view the explanations given after the due date.

Student Performance

A successful teaching and learning tool should improve student performance. We first implemented the CAPA system on a trial basis in the large-enrollment, upper-division, lecture-laboratory course, Introductory Plant Physiology (Botany 301) taught by colleagues in the Fall 1996 semester. Three mandatory CAPA assignments were given (two covering plant water relations and one covering basic Mendelian genetics and physiological genetics). The students were given 2 weeks to complete each assignment and allowed unlimited tries to answer each problem correctly. The mean score was 28 out of 30 points possible (94%, $n = 60$). A complete set of 13 mandatory CAPA assignments was implemented the following Spring (1997) semester. The students were allowed 1 week to complete each assignment and were limited to 10 tries per problem. The mean score was 137 out of 172 possible points (80%, $n = 88$). Difficult or troublesome problems were rewritten or replaced for the next trial (Spring 1998), when the mean score on the edited set was 172 out of 185 possible points (93%, $n = 62$).

Performance on CAPA homework correlated with performance on lecture examinations in the Spring 1997 semester ($r = 0.6136$; not shown). Because questions derived from CAPA homework problems were only a part of the examinations in 1997 and 1998 (Table IV), this moderate correlation was not unexpected. The correlation between homework scores and final-examination scores in physics classes in which CAPA was used for all homework sets, quizzes, and examinations was only 0.300 (Kashy et al., 1998). There were eight students (9%) in our plant physiology course who scored very high on the homework but did not perform well on the examinations. These students may have needed more time to think through problems. There are several features of CAPA (immediate feedback, multiple tries, on-line hints) that give students at all levels of ability the opportunity to succeed if they give enough time and effort.

Our data clearly indicate the beneficial effect of mandatory homework sets on student performance on examinations. When the plant physiology course was taught in 1995, there was mandatory, hand-graded essay homework. In 1996, the hand-graded homework was optional rather than mandatory; by 1997 and thereafter, mandatory CAPA sets were used. The mean scores on equivalent examinations for the 4-year period from 1995 to 1998 are given in Table III. These data indicate that students performed better when given mandatory homework. There is a statistically significant difference between the examination scores in 1996 and the scores in 1995, 1997, and two of the three examination scores in 1998 ($P < 0.003$). There were no significant differences between equivalent examinations in

Table III. *Comparison of mean examination scores ± SD over 4 years*

In 1995, students turned in 10 mandatory essay homework assignments that were hand graded; in 1996, the same homework assignments were optional; in 1997, 13 mandatory CAPA assignments replaced the traditional homework. The subject material covered on each lecture examination was the same each year. The differences between the "a," "b," and "c" values are statistically significant (see "Materials and Methods"). (Comparisons were made horizontally only.) Values in parentheses are nos. of students taking each examination.

Examination	Spring 1995: Required Hand-Graded Homework	Spring 1996: No Required Homework	Spring 1997: Required CAPA Homework	Spring 1998: Required CAPA Homework
			%	
1	73 ± 13.0a (70)	58 ± 16.5b (84)	71 ± 15.6ac (88)	67 ± 13.9c (60)
2	65 ± 17.4a (68)	57 ± 16.4b (83)	70 ± 13.5a (85)	65 ± 14.0a (61)
3	70 ± 12.9a (67)	65 ± 13.7b (79)	71 ± 14.3a (84)	68 ± 12.1ab (60)

1995 and 1997 or 1997 and 1998, and two of three of the comparisons were not significantly different between 1995 and 1998. Thus, scores on five of the six examinations given when CAPA was in use significantly exceeded equivalent examination scores from when there was no mandatory homework. Examination scores from when CAPA was used were similar to scores from when hand-graded essay homework was required. Scores on eight of the nine examinations given when homework of either format was required were significantly higher than scores on comparable examinations given when homework was not mandatory. These data suggest that mandatory homework improves student performance on examinations.

In principle, other variables might have affected student performance on examinations in this class. Among them are student response to different instructors, changes in the laboratory component of the class and its valuation in the final grade, and changes in examination format. However, the course was taught by K.D.N. for the semesters reported, and the laboratory component and its weight in the determination of final grades were unchanged. The examination format (relative weighting of short answers or CAPA questions to essays) varied between comparable tests in different semesters and between different examinations in the same semester (Table IV), but the conceptual material covered in the essay questions did not change. Comparison of the data in Tables III and IV reveals no relation between examination format and student examination performance. In Spring 1996, when no homework was required, the three tests contained short-answer sections valued at 40, 42, and 41 points, whereas in Spring 1997, when CAPA homework was mandatory, the corresponding CAPA sections were valued at 46, 46, and 50 points; yet, student examination performance in these 2 years differed significantly (Table III). Student mean examination scores were, with one exception, not significantly different in 1997 and 1998 when CAPA homework was required in both semesters (Table III) but the examination formats were different (Table IV). Similarly, student examination performance in 1995 was not significantly different from that in 1997, but the valuation of the short-answer section of examinations in 1995 was variable, often quite different from the valuation of the CAPA section of the examination in 1997. We find no evidence that relates superior student examination performance to changes in instructor, laboratory part of the course, or examination format. We conclude that mandatory homework improves student performance on examinations, with CAPA effectively substituting for traditional hand-graded homework in plant physiology.

Table IV. *Examination formats over 4 years*

Examinations consisted of an essay section and a short-answer section (matching, true-or-false, and multiple-choice questions). This format was replaced in 1997 and 1998 with comparable questions derived from CAPA homework problems. The point values for the short-answer section or the CAPA section (points/total points on test) for each examination in these semesters are listed.

Examination	Spring			
	1995	1996	1997	1998
1	49/105	40/105	46/100	66/100
2	68/104	42/102	46/100	65/100
3	74/100	41/100	50/100	60/100

Moreover, CAPA has several important advantages compared with traditional hand-graded assignments. Grading time is greatly reduced, which frees the instructor to help students. There is a favorable shift in student attitude toward the instructor. Rather than viewing the instructor as an evaluator, students consider the instructor as a resource and coach, assisting them in answering the computer questions. We also found that with CAPA it was feasible to cover a broader range of subject material and include more challenging material on homework and examinations. Before we adopted CAPA for homework assignments, our students struggled with homework problems at the first (knowledge) and second (comprehension) levels of cognition (Bloom et al., 1956). With CAPA, we included problems at the highest levels of cognition and students successfully answered them. Thus, although mean examination scores generally were not significantly different with hand-graded versus CAPA homework, course standards and overall learning were increased by implementation of CAPA.

Other Computerized Learning Systems

We are not aware of published reports of similar systems in use in plant biology courses per se. However, various innovative computerized learning systems are being used in other life science courses. Two categories of software that generate interactive programs are used in biology study centers at the University of Michigan (Kleinsmith, 1987). One generates multiple-choice problem sets designed to help students apply concepts learned in lecture, and the other creates dynamic animations of biological processes. The BSCS individualizes problems by randomizing the order of the choices within each problem, but it does not have different variants for each choice, as CAPA does. With the many variants of each CAPA problem, students cannot simply exchange answers; rather, they are encouraged to discuss concepts together. Both CAPA and BSCS are interactive, which is an aspect that contributes to their success and popularity. Both systems provide immediate feedback on the correctness of a response, and both allow multiple tries. The feedback provided by BSCS points out errors in reasoning for each wrong choice and explains the right answers. CAPA provides hints to help direct the student to the correct answer, and explanations for answers are often available after the due date. These forms of feedback help students develop reasoning skills and allow the use of more challenging problems. A remarkable 97% of the 500 introductory biology students at the University of Michigan make use of the study center tutorials, even though they are optional. Since the implementation of BSCS, mean examination scores have increased by 15%.

Another novel learning and assessment tool used for more than 70 subjects at universities in Australia is BrainZone (Strassburger, 1997). This World Wide Web-based tool is used to create questions (multiple choice or short answer) that students can access from any on-line computer at any time. Students log on to the site, enter an access code and password, and select a subject and topic. BrainZone gives them a random set of questions to work through and provides instant feedback. BrainZone may be used in either a "learning mode" or a "testing mode." In the learning mode, students may repeat tests as many times as they wish, each time receiving a unique set of problems. As with CAPA, the instructor is able to monitor student progress and study habits and can identify questions that give students the most difficulty. Early evaluations of BrainZone revealed improved study habits on the part of students and improved performance on examinations. Students rated BrainZone very favorably.

To our knowledge, we have described the first application of CAPA software in the life sciences. Previous applications of CAPA have been limited to the physical sciences (Kashy et al., 1993, 1998; Morrissey et al., 1995; Thoennessen and Harrison, 1996), although recently it has been implemented in courses as diverse as Family and Child Ecology and Human Food and Nutrition (see http://www.pa.msu.edu/educ/CAPA/). CAPA is adaptable to many fields because of the variety of formats available for writing qualitative problems. Students rate CAPA positively as a useful learning tool. Our CAPA plant physiology problems are available to other institutions, and anyone interested in adopting CAPA for a plant physiology course should contact K.D.N. For other courses, see http://www.pa.msu.edu/educ/CAPA/.

APPENDIX

Problem	Figure 1A (Artus)	Figure 1B (Nadler)	Figure 2
1	ABDEF	ACDEG	abd
2	FVFFFV	VVFVVF	a
3	DADCB	CADBB	
4	ACBBAADA	BDCCCCDA	
5	BEDACF	FCEADB	
6	9,F	9,F	

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