

# An Inquiry-based Approach to Teaching Plant Physiology

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**SUMMARY.** The principles of plant physiology are best learned in an environment where students are directly engaged in the process of scientific inquiry. Working from this assumption, we have developed a two-stage approach to laboratory instruction that fosters student-directed research within an undergraduate plant physiology course. During the first 10 weeks of a 16-week semester, students develop competency in measuring physiological variables by using an array of standard analytical techniques. A core set of 10 laboratory experiments provides structured instruction and teaches the principles of modern physiological analyses. During week 11, students observe a demonstration of a plant response, where the underlying cause of the phenomenon is not evident. Working together in groups of three or four, students hypothesize on the physiological mechanisms that may be involved. After submitting a statement of hypothesis and a plan of study, each group then requests the necessary instrumentation, plant material and greenhouse and/or growth chamber space to conduct their experiments. Results of their experimentation are presented during week 15 in both written and oral formats. The approach appears to help students to integrate and connect learnings from earlier in the semester to solve a defined problem. Further, students learn how to judge the reliability of experimental results and to evaluate whether conclusions drawn are justified by the data.

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An important goal of any teacher of plant physiology is to engage students' innate curiosity about plant function, development and responsiveness to environment cues. To accomplish this goal in a way that is exciting and that enriches a student's view of the natural world, the teacher needs to maintain an appropriate balance between conveying factual, disciplinary knowledge and fostering active student engagement in the process of scientific inquiry (Allen et al., 1986; Arons, 1993; Lee and Jones, 1993). This premise formed the basis of our approach to teaching plant physiology in HORT 301 (Plant Physiology), a four-credit undergraduate course at Purdue University. During 1994-1999, we developed a two-stage approach to laboratory instruction that first seeks to develop a working knowledge of analytical techniques and then encourages student experimentation to solve a genuine scientific problem. Our experience with this approach is outlined below. A more detailed description that focuses on an example problem is provided by Joly et al. (2000).

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## An inquiry-based approach to learning

First, a core of 10 laboratory experiments has been designed to complement and reinforce the concepts and processes introduced in lectures. The objective of the core labs is to provide structured experience with the tools used to study plant physiology and to teach the principles and skills used in modern techniques of measurement. These labs include methods and instrumentation from the fields of biophysics, biochemistry and molecular biology, because these fields are, to a large degree, the principal tools of the plant physiologist. Laboratory exercises include: plant enzymology, pigment quantification, chloroplast physiology, measurement of CO<sub>2</sub>- and water vapor exchange, protein analysis, measurement of plant water potential and its components, estimation of turgor in higher plants, measurement of chlorophyll fluorescence induction kinetics, observation of growth responses to plant hormones and measurement of the hormone ethylene. Written lab reports conform to standard methods for presentation of experimental results, and students are asked to focus on questions raised by the data that could be explored by further experiments. In summary, the goals of the core sequence of labs are to provide the technical skills for probing plant physiological systems and to reinforce the idea that many unresolved questions occur in plant physiology.

The second phase of the laboratory (weeks 11–15) provides students with a chance for active, personal participation in the process of inquiry. At present, most laboratory exercises in plant science courses conform to the following format: conduct a highly defined (cook book) experiment, observe the results, offer explanations. These exercises are seldom true experiments based on a new hypothesis, but rather exercises designed to illustrate a well-established principle. The approach may be useful in illustrating the concepts and processes under discussion, but it is generally devoid of the sense of excitement that comes from real experimentation and discovery (Tinnesand and Chan, 1987).

Accordingly, during the tenth week of class, students are presented with one or more demonstrations of

plant behaviors or responses, where the underlying cause of the phenomenon is not evident from simple observation. Students are asked to observe the response or condition and to offer explanations and hypotheses regarding how and why the plant has responded as it has. The examples are chosen in order to illustrate that experimentation will be needed to resolve alternative possibilities. Demonstrations may focus on physiological changes that occur during development, responses to environmental factors (water, light, temperature, humidity), transitions between vegetative and reproductive phases or on physiological differences arising from specific mutations. The specific examples chosen vary from year to year, and generally are suggested by recent developments in the discipline or from the instructors' own laboratories. Problems are selected such that substantive answers to focused questions can be obtained within 1 month.

Students work together in groups of three or four to observe the response in question, consider possible explanations and hypothesize on the underlying mechanisms that may be involved. This activity is meant to be fully participatory. Course instructors as well as two graduate teaching assistants are present at these sessions to serve as information resources and to make suggestions. Comments are made judiciously to afford students the maximum opportunity to develop the skill of formulating questions. The nature of the guidance provided is critical to the quality of learning attained, and it is important that instructors use restraint during this period (Joly et al., 2000). Each group presents a plan of study to the instructors, where hypotheses and experimental approaches are defended. Constructive criticisms at this stage may result in the formulation of new experiments or reconfiguration of the original plan. After a written plan of study has been approved, the student groups will initiate their research projects.

Each group has considerable autonomy in their conduct of the research. They may pursue several experiments simultaneously, where each is designed to answer a discrete hypothesis. More commonly, however, groups choose to conduct a logical sequence of experiments over a 3-week period, where the direction of

inquiry will be dictated by what has been learned at each step. In short, the structure permits open-ended inquiry. The scientific method does not end when an answer has been found or when a particular (known) function has been described. Rather, the process of inquiry continues: initial results are characterized and explained, new hypotheses are constructed and new experiments are designed.

Results of the experimentation are presented during the final week of classes (week 15). A final written report is required of each student, and all group members participate in a 20-min oral class presentation. The instructors lead discussions that attempt to dissect and evaluate reported information. The objective of this activity is to improve students' ability to judge the reliability and significance of experimental results and to evaluate whether the conclusions they have drawn are justified by the data.

## Student learning

The problem chosen for inquiry-based student research in 1996 and 1997 focused on chilling injury in tomato (*Lycopersicon esculentum* Mill.) seedlings and on the possible role of catalase in ameliorating the damage (Joly et al., 2000). The student learning from this experience can be classified into practical knowledge and higher-order understanding.

On a practical level, students learned of the need for care in experimentation. They learned that experimental errors must be minimized if treatment effects are to be separated statistically. Further, the class as a whole learned from a small number of particularly observant individuals who noticed subtle differences in plant responses that, in turn, led their group toward more productive experiments. Finally, students learned to plan and use resources efficiently and to divide responsibilities among group members to accomplish their goals.

Students learned during the month-long inquiry project that scientific inquiry is a *process*. Importantly, they learned how new knowledge is derived from novel experiments and that the hypothesis is the principal intellectual tool in research. In 5 years of experience with this approach, we have found that an overwhelming majority of students have had little, if any, experience in developing a falsifi-

able hypothesis and then designing a specific experiment to test their ideas. John Dewey (1995) wrote in 1909:

“Science teaching has suffered because science has been so frequently presented as just so much ready-made knowledge, so much subject-matter of fact and law, rather than as the effective method of inquiry into any subject-matter.”

The approach outlined here attempts to help students experience science in a richer and more realistic context. The new laboratory environment is sometimes frustrating for students who are more comfortable in a more highly structured setting (Spears and Zollman, 1977). For example, students learn that experimental results often are inconclusive. They learn that their hypothesis may have been naive or based on faulty assumptions. However, because they have the time to construct a new hypothesis and design a second or third experiment, they begin to function as though they were plant physiologists engaged in elucidating a true problem. Students learn how to apply their acquired knowledge to the next experiment, and they begin to recognize that if the data did not support their hypothesis, that outcome was not itself a failure. In short, they have encountered an authentic scientific problem, and they have experienced science as a method not as a simple body of facts.

Students' capacities for analytical thinking and problem solving appear to be enhanced through this experience. Students must make informed decisions based on what they see and measure, and *they* must choose among alternative lines of inquiry. They learn how to sift the most relevant information from their initial experiments and from the scientific literature. From this process, they may discard their first hypothesis and attempt to test a new

one. Because they may need to draw upon concepts from throughout the course in order to design effective experiments, the inquiry-based approach appears to help students integrate and connect learnings from earlier in the semester to solve the problem.

Finally, because students experience firsthand the practical difficulties of measuring physiological variables, they learn to be cautious in interpreting their results as well as prudently skeptical of the results of others. Student questions posed to each other during the final oral reports revealed that many had developed a capacity to question the reliability of experimental results and to evaluate whether conclusions drawn by others were justified by their data.

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