

level and its physiological relevance within a tissue or a complete organism. While a treatment of physiological regulation may seem a bit beyond the announced scope of the book, it undoubtedly represents the next step toward a more integrated understanding of these processes. In this respect, a chapter on the physiological control of body size, as well as on its pathological deregulation in humans, would have added a significant and medically relevant component to the discussion of growth control.

The final chapter evokes some fascinating features of plant growth, including the surprising “solid” and “liquid” growth concepts. Solid growth refers to growth taking place in the meristem (cytoplasmic cell growth and cell proliferation), and cell expansion (due to a dramatic accumulation of water in the cell), which accounts for most of the mass of the plant, is called liquid growth. The chapter mostly focuses on the mechanisms that control meristematic cell growth and proliferation, which

provide the cells that form the plant. Growth control is emerging as an important issue in plant research, and the recent sequencing of the *Arabidopsis* genome should accelerate the discovery in this area.

In conclusion, the publication of this book coincides with the onset of a new era in growth studies, and it should be of great use for helping students and researchers appreciate growth as a regulated process playing key roles in many developmental, physiological, and pathological events.

Pierre Léopold
Institute for Signaling, Developmental
Biology, and Cancer
UMR6543 CNRS
Parc Valrose
06108 Nice Cedex 2
France

Clickers: A Teaching Gimmick that Works

One study after another over the past decade has shown that students who engage interactively with each other and the instructor in the classroom learn concepts better, retain them longer, and can apply them more effectively in other contexts than do students who sit passively listening, perhaps taking notes for future memorization in preparation for an exam (evidence reviewed in Handelsman et al., 2004, *Science* 304, 521–522). This general principle applies at all educational levels, from primary school through college and graduate courses. At many primarily undergraduate institutions (PUIs), where teaching is the primary responsibility of faculty members and class sizes tend to be small, these findings have driven widespread transformation of science teaching from lectures to seminar-style courses consisting primarily of student projects, presentations, discussions, and exploration of case studies that require students' active participation. By contrast, in the large research universities (RUs), where many faculty see research as their primary responsibility and teaching as a distraction and where class sizes tend to be large, lecture classes have generally remained the norm for undergraduate science teaching in core courses.

Does this matter? The so-called “Oberlin Report” from the 1980s showed that a disproportionately high percentage of students who went on to pursue graduate study in science received their baccalaureate training at PUIs (see more recent data at <http://www.nsf.gov/sbe/srs/seind04/start.htm>). We at the RUs must do a better job of encouraging and training our science students.

Science faculty and administrators at RUs have generally assumed that lecturing in an auditorium setting is the only feasible teaching format for large courses in view of faculty time limitations. However, recently developed tools using simple information technology make it possible, with little extra faculty effort, to conduct

even large classes in which students interact with the instructor and each other in a much more lively fashion that promotes active learning. One of these technologies is personal response systems, colloquially termed “clickers.” These systems can not only provide valuable feedback to both instructor and students during a class, but can also facilitate changes in both student and instructor behavior that enhance teaching and learning, as described below.

Several different brands of these systems are available, but all of them consist of clickers (transmitters), operated by students, which can send infrared or radio frequency signals to one or more receivers that feed into a computer controlled by the instructor. Some brands use wall-mounted receivers hard-wired to the computer, while others are portable and entirely wireless. The clickers are small hand-held devices resembling a TV remote, with several buttons labeled numerically or alphabetically. Students typically buy the clickers for \$5 to \$30 at the campus bookstore at the start of the semester and register them online with the course software, which links the serial number of each clicker to the name and email address of the student. In class, when the instructor poses a multiple-choice question and asks the students to respond, each student clicks an answer, which is picked up by the receivers and stored with the student's records by the software. The software can instantly display a histogram of the students' answers, which can be displayed to the class with a data projector. The software also allows the instructor to later look up the responses of an individual student to each question, and it can be programmed to assign credit points if desired and even to email point totals to students. The cost to students is minimal, since a clicker can be used in more than one course, and most bookstores will buy back used clickers at the end of the semester. Cost to the department for receivers and software is roughly \$1000 per 100 students in a classroom.

Like any technology, these systems are intrinsically neither good nor bad; they can be used skillfully or clumsily, creatively or destructively. However, they can

produce results that are eye-opening and potentially of great value to both students and instructors for enhancing the teaching-learning process. I will illustrate their use with an example from my own experience.

I became sold on clickers in teaching Developmental Biology to a class of about 75 juniors and seniors a year ago. I particularly remember one class near the start of the course on the molecular genetics of maternal-effect mutants, something our students always seem to find difficult to understand. As an example, I was using *C. elegans*, which they were working with in the lab. I had spent about 20 min using PowerPoint images and diagrams to explain the hermaphrodite reproductive system, how genes that encode proteins essential for embryogenesis are expressed and the proteins incorporated into eggs only in the female germline during oogenesis, and why, therefore, recessive embryonic lethal mutations in these genes affect the embryo only if the maternal parent is homozygous mutant, regardless of the embryo's genotype. To check whether they had noted this rule, I posed a simple multiple choice question: would the viability of an embryo resulting from a cross that involved such a mutation depend on (a) the genotype of the mother, or (b) the genotype of the embryo. Over 90% clicked the correct answer (a). Then I gave them a pedigree in which F2 embryos were produced by a heterozygous F1 hermaphrodite, so that if *m* is the embryonic lethal mutation, there would be F2 embryos of three genotypes: $+/+$, $m/+$, and m/m . From questioning the class as a whole, it seemed clear most students understood that the first two genotypes would be viable. Then I posed a clicker question: would the m/m embryos (a) live or (b) die. The students voted individually, and the histogram showed (a) 48%, (b) 52%. From the students, there were some nervous giggles. For me, this was a moment of revelation. I was not so much disappointed by the result as elated by the realization that for the first time in over 20 years of lecturing I knew, on the spot (rather than after the next mid-term examination), that over half the class didn't "get it:" had not understood either the question or my presentation of the phenomenon. Because I had already explained the phenomenon as clearly as I could, I simply asked the students to debate briefly with their neighbors and see who could convince whom about which answer was correct. The class erupted into animated conversation. After a few minutes, I asked for a revote, and now over 90% gave the correct answer (a).

What happened? During the discussion it came out that some students were relying on a preconception, probably from previous genetics courses, that an animal homozygous for a recessive embryonic lethal mutation cannot live, because they hadn't processed my explanation for how this is possible. Others misunderstood the question or interpreted it sloppily, and answered (b) because they confused viability of the F2 m/m animals with the viability of their progeny F3 embryos, which will all die. Whatever the reasons for the wrong answers, most were corrected by the process that Harvard physicist Eric Mazur calls "Peer Instruction" (<http://mazur-www.harvard.edu/education/>); the students were better at clearing up each other's confusions and misconceptions than I as the instructor could have been.

This example illustrates two uses of clicker questions: (1) to find out whether students are paying attention to the extent of hearing or noting down a stated rule, and (2)

to find out whether they can use a previously explained concept in a somewhat different context to solve a problem or predict an outcome. The clickers are particularly useful with PowerPoint or similar programs, where questions asking for interpretation of an image or a graph or table of data can be incorporated into the presentation. Another use is to lead students stepwise through a complex process, for example, generation of a homozygous mutant mouse starting from embryonic stem cells in which a gene of interest has been knocked out or knocked in. Instead of simply hearing a description of the process, students are asked with multiple choice questions, followed by group discussion where there is substantial disagreement, what they should do next at each step in view of the desired goal. This way, they must think through each of the steps in the process, rather than simply writing them down for later memorization before a test.

The above advantages of using clickers in a large class, plus a few more, are summarized below for both students and instructors.

For the students:

- They are answering anonymously—no one has to worry about the possible humiliation of giving a "dumb" answer.
- Those who did not "get it" realize they're not the only ones. In a typical lecture situation, such students are often inhibited from asking a question by the belief that "everyone but me probably understood."
- Those who apparently did not "get it" often find out the reason was not their lack of knowledge, but an unclear or ambiguous question from the instructor.
- Most important, the students are actively engaged with the topic at hand and, therefore, more likely to understand and retain it better than if they were only sitting passively and listening to the instructor.

For the instructor:

- S/he can later find out from the software which students are present and give credit, if desired, for in-class participation.
- S/he knows immediately, in real time, what fraction of the students didn't "get it," information that often does not become apparent in a standard lecture course until after the next exam, when it's too late to do much about it.

Nevertheless, not all students like the clickers. Although the majority warmed up to them during our course, a small minority continued to be negative. We have some evidence that this resulted from the "big brother" aspect, that their responses were all being recorded and stored in the instructor's database. Probably more significant, they had to come to class in order to receive points for participation (a significant fraction of their course grade), and to pay attention while they were there.

Not all instructors will like clickers either, and how they are used will depend on the individual and his or her tolerance for student input and some disorder during class. For example, when half the class has chosen a wrong answer, one option is simply to tell them the correct answer and move on. In my opinion, this would be a great teaching opportunity lost, and would negate use of clickers as a tool to increase active engagement. Another option is to explain the concept again, preferably in a different way. This is better, but the students are still sitting passively and taking notes. The third

option, inviting students to convince their neighbors of their point of view as described above, seems to me by far the most effective. When a split vote occurs, the tension and desire to resolve it are almost palpable, and students have an emotional as well as intellectual stake in doing so.

The group interaction that this use of clickers encourages is difficult in the auditorium-style lecture halls where virtually all large classes are taught; there is a great need for RUs also to provide more large classrooms with flexible seating. Regardless of the seating arrangement, however, the use of clickers can lead to a substantial increase in student active engagement during class. They offer the possibility of further transforming courses to the point where information transmitted by the instructor is no longer the major use of class time. Instead, students are assigned reading and diagnostic problems in advance and required to post answers on the course website before class, so that the instructor can direct classroom activities to addressing

difficult aspects of the material through interactive exercises (<http://webphysics.iupui.edu/jitt/jitt.html>).

On the other hand, an instructor convinced of the value of lectures and reluctant to change teaching style can use the clickers in a lecture context as above, simply to obtain valuable real-time feedback on concepts that students have difficulty with. The give-and-take atmosphere encouraged by use of clickers in our experience makes the students more responsive in general, so that questions posed to the class as a whole during a lecture are much more likely to elicit responses and discussion. For this reason, incidentally, teaching with clickers is a lot more fun!

William B. Wood
Department of MCD Biology
347 UCB
University of Colorado
Boulder, Colorado 80309

How Does Novelty Emerge through Scientific Investigation?

Investigative Pathways: Patterns and Stages in the Careers of Experimental Scientists
By Frederic Lawrence Holmes

New Haven, CT: Yale University Press (2004)
256 pp. \$35.00

What are preconditions for scientific creativity? Can we regard changes in scientific knowledge as occurring as sudden shifts, as a series of revolutionary moments, or is the main feature of scientific development better described as a process of continuity? What is a scientific discovery? Do so-called Eureka moments exist—experiences in which scientists have flashes of new insights that reveal the essence of a new theory? Or should we think of a new discovery as the outcome of a long-term daily routine of scientific experimentation?

These questions that lead to the central problems addressed by historians of science are raised and discussed by Frederic Holmes in his latest book. *Investigative Pathways* is a book that both analyzes biographical patterns of several outstanding experimental scientists from the 18th to the 20th century and also provides a stimulating discussion of the main epistemic approaches taken up by history of science of the last decades.

With the term “investigative pathway,” Holmes introduces a concept that lies at the center of his historical and epistemological approach: “The investigative pathway may be, at its most basic level, only the scientist version of the metaphor of life as a journey” (p. xviii). Written shortly before his death, Holmes’ last book is itself a reflection of his own 45-year-long journey as a historian of science. Thus, for all readers who do not know Holmes’ important books on *Claude Bernard and*

Animal Chemistry ([1974] Cambridge, MA: Harvard University Press); on *Lavoisier and the Chemistry of Life* ([1985] Madison, WI: The University of Wisconsin Press); his detailed reconstruction of the work of biochemist Hans Krebs on the intermediary metabolism (*Hans Krebs: The Formation of a Scientific Life, 1900-1933*. [1991] Vol. I, Oxford University Press; *Architect of Intermediary Metabolism, 1933-1937*. [1933] Vol. II, Oxford University Press); or, more recently, his exhaustive analysis of the research of three molecular biologists, Seymour Benzer, Matthew Meselson, and Frank Stahl (*Meselson, Stahl, and the Replication of DNA*. [2001] New Haven, CT: Yale University Press), this book offers a dense introduction into what Jed Buchwald has called in his afterword the “Holmsian pattern” (p. 193): the reader will gain insight into the work of one of the preeminent scholars in the recent history of science, whose own research life was devoted to understanding the complexity of how novelty emerges in experimental science, whose books have set standards, and whose methodological approach has been shaping the direction of the history of science decisively during the last decades.

Science is a collective as well as an individual endeavor. Holmes emphasizes that the metaphor of “investigative pathways” provides a framework to understand the development of scientific research, taking into account this double character of the scientific enterprise. For exploring the scientific endeavor, from the level of broad investigative streams formed by the collective work of scientists engaged in a specific discipline, up to the finer level of the daily research activities of an individual scientist, Holmes differentiates three analytical scales of reconstructing the investigative pathways of experimental scientists: (1) a broad scale that examines different phases over the lifetime of a career, such as apprenticeship, mastery, distinction, and maturity; (2) a middle scale that deals with episodes of a shorter time span within such a career; and (3) a fine scale that tries to reconstruct the day-to-day research