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THE BEST WAY FOR STUDENTS TO LEARN science is to experience challenging problems and the thoughts, habits of mind, and actions associated with solving them. Problem-based learning (PBL) is a powerful vehicle for inquiry-based learning in which students use an authentic problem as the context for an in-depth investigation of what they need and want to know (Checkly, 1997). This robust, constructivist process is shaped and directed primarily by the student, with the instructor as the "thinking" coach.

PBL is not just a reiteration of what many science educators already use in their classrooms. To be truly problem-based, three key features must be present in a lesson: initiating learning with a problem, exclusively using ill-defined problems, and teachers acting as "thinking" coaches (Gallagher, 1995).

ILL-DEFINED PROBLEMS

At the heart of true PBL is an ill-defined problem—an unresolved, murky situation. This problem is presented to small groups of students who have stakeholder roles—the hooks that propel and involve students in the ill-defined situation (Gallagher, 1995).

To better understand what is meant by an ill-defined problem, it is helpful to examine what is meant by a problem. Although problems can differ, they all have three characteristics—an initial or present state from which to begin, a goal state to be achieved, and a set of actions or operations needed to get from the initial state to the goal state.

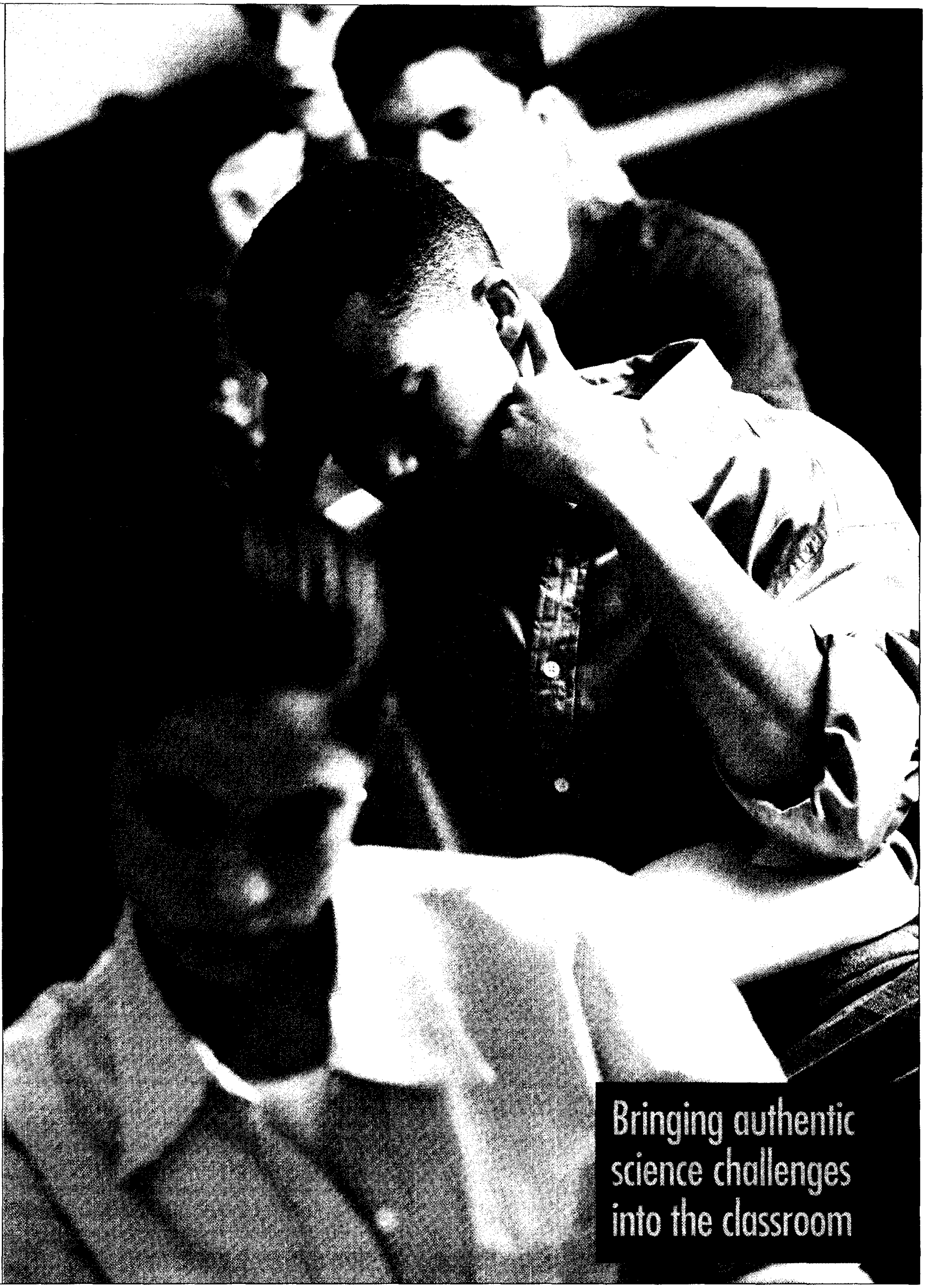
While all problems have these components, they often differ in how well defined they are. Problems can vary on a continuum from relatively well defined to ill defined for each of these components. In PBL, the problem is ill defined with respect to all three characteristics, which is typically how problems present themselves in science. The problem is unclear and raises questions about what is known, what needs to be known, and how the answer can be found. Because the problem is unclear, there are many ways to solve it, and the solutions are influenced by one's vantage point and experience.

In typical classroom problem solving approaches, students encounter problems after all information is taught, giving the misleading impression that problems arise only in circumstances where all information needed for solution building is available. In PBL, the order of learning is inverted to reflect authentic learning and problem solving (Gallagher, 1995). Learning begins only after students are confronted with the problem.

TEACHING FOR UNDERSTANDING

One theme of science education reform is understanding that science involves ways of thinking and doing as well as bodies of knowledge. Emphases are placed on thinking, problem solving, and habits of mind that promote exploration and discovery such as curiosity, questioning, openness to ideas, learning from errors, and persistence. Learning needs to occur in the context of real investigation through inquiry and reasoning, which means teaching for understanding, not memorization of facts (American Association for the Advancement of Science, 1989; National Science Teachers Association, 1992).

Learning specialists concur. Learning is best, and much more takes place, when the learner is the one to look deeply to create meaning and understanding (Wiggins and McTighe, 1998). Understanding is deep learning that goes well beyond simply knowing; it means doing thought-



Bringing authentic science challenges into the classroom

FIGURE 1.

Scenario for an ill-defined problem.

You are invited guests to a cancer research presentation in the hospital conference room. Your organization, Science in the Public Interest, does more than report medical research findings to the public. It questions them and actively explores further meaning for public consideration. You listen carefully as "Programmed to Die" begins.

"Metastasis . . . cells dividing out of control. That's what kills us. Finding a cure for cancer is a difficult problem because all cancers aren't alike. I'll make the analogy to infectious diseases like HIV and influenza. Their treatment and how they cause disease differs. Colon cancer behaves differently than melanoma, which behaves differently than prostate cancer. While some things are similar, like cells dividing out of control, they behave differently. Melanoma likes to go from the skin to the brain and liver, not to bone or lung. Colon cancer goes to the liver, breast cancer to lung, bone, and brain. It's like these cancers have zip codes. There's selectivity as to where they go and set up shop. There's a 95 percent cure rate for testicular cancers. Hodgkin's disease once had a bad prognosis, now 90 percent survive. But this doesn't apply to breast cancer or other important diseases.

"We've been studying metastasis by looking at genes that are expressed in a tumor cell versus its metastatic components to understand the molecular differences between the original tumor and one that went to the liver. En route, we discovered a new gene that keeps a melanocyte in its normal state and tends to prevent its progression to melanoma. As melanoma develops, this gene is no longer expressed. In science, you often pursue directions that are different from your primary focus and wind up discovering things that might be related, like a gene that's important in the fruit fly or worm that's also found in humans. In the worm, we discovered something we call programmed cell death, which is an exploding area of cancer research.

"In the development of the worm there are certain cells. When cells divide in twos, one gets discarded and dies. It's meant to die. If not, it's a problem. If a cell's DNA is damaged and isn't repaired, it's supposed to die. If not, it leads to cancer. Not all cells produced are meant to continue to be produced. Normally, you divide the two. Each one should have a function. We did experiments to interfere with that, and the animal's whole system became abnormal. If cell death is important in a worm, what happens in humans when cells that should die don't? Normally, when a cell is damaged, there's a mechanism for repairing it or getting rid of it. A cell dying by this mechanism looks different from one dying from other causes.

"A connection between AIDS and cancer is the immune system, the National Guard that protects our shores. Cancer cells are probably being produced all the time, but there's a lot to suggest that the appropriate immune cells get rid of them. When the immune system is suppressed, and the National Guard troops have gone from thousands to ten, invaders come ashore and set up shop. There aren't the natural killer cells and macrophages that get rid of cancer cells, resulting in malignant tumors that metastasize. The immune system is important but not the whole story in understanding metastasis.

"In the future, we'll be better able to determine the behavior of tumors through molecular testing. A cancer cell grows out of control. Through gene therapy, which is being tried now, we'll try to put those controls back in by reintroducing genes that either were lost or nonfunctional to regain behavior. Meanwhile we're searching for other solutions" (Isselbacher, 1998).

demanding activities, finding evidence, and interpreting information in new ways (Perkins and Blythe, 1994). Students need to uncover content for meaning, to question and verify ideas if they are to be understood (Wiggins and McTighe, 1998), and their minds need to be purposeful, self-reflective, creative, and free to create meaning (Caine and Caine, 1997). For these reasons, a priority in teaching for understanding is to shape content in ways that help students make sense of it through inquiry and application (Wiggins and McTighe, 1998).

PBL involves a shift in roles for students and teachers. The student, not the teacher, takes primary responsibility for what is learned and how. The teacher raises questions that challenge students' thinking and help shape learning so the search for meaning becomes a personal construction of the learner. Understanding occurs through collaborative, self-directed, authentic learning, characterized by problem solving, reiteration, and self-evaluation. This is what distinguishes true PBL from other methods that use a problem of any sort somewhere in the teaching and learning sequence (Barrows, 1997).

When students encounter a problem as it occurs outside the classroom, they are often surprised to find there is insufficient information to develop a solution, no single right answer or strategy, and a need to redefine the problem as new information is gathered. Ultimately, students cannot be sure of their solutions because information is still missing (Gallagher, 1995). This inconclusiveness characterizes science, which one scientist describes as "a process of thinking about problems then designing means of approaching them . . . not necessarily to solve the problem you outlined, but to make an inroad or a start, asking what further approaches can I use to get a handle on this problem?" (Isselbacher, 1998).

CONNECTING STUDENTS WITH SCIENTISTS

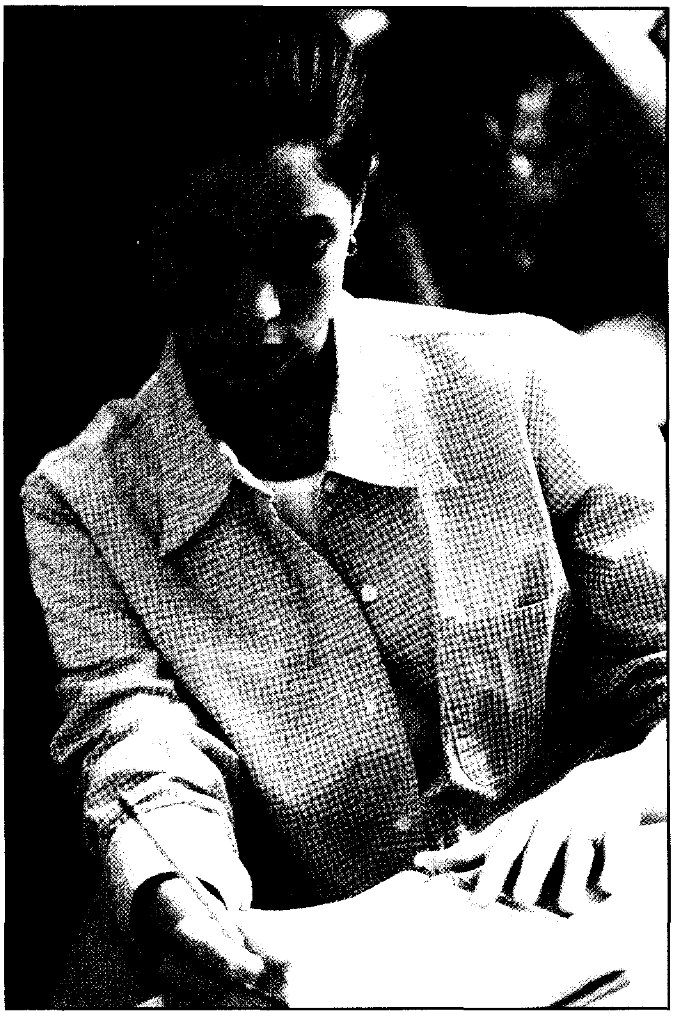
An exciting way to launch students into the process of science and expose them to ill-defined problems is to introduce them to practicing scientists and their work. I interviewed six prominent biomedical scientists and asked each to describe an especially challenging research problem. They also discussed their concept of science and important thinking behaviors of scientists. Students need to learn firsthand about this private side of science—the essential habits of mind and thought processes that promote exploration and discovery.

Each scientist discusses perplexing aspects of their particular research, which may be on cancer, organ transplantation, heart disease, AIDS, the treatment of wounds and burns, substance abuse, or human responses to environmental toxins. Embedded in these talks are problems students can unearth and investigate using the steps in the PBL model. Examples of the model's application by a group of biology students follow.

TEN STEPS TO PBL

The following approach, which is based on a popular medical school model of PBL, involves students in constructing understanding through critical and creative thinking and promotes collaboration and autonomy in learning (Barrows, 1986):

- **Encounter an ill-defined problem:** Students can encounter real-life, ill-defined problems in many compelling contexts. In the scenario outlined in Figure 1, biology students are given stakeholder roles as members of a special interest group who are listening to the presentation "Programmed to Die," given by the teacher, who is playing the part of one of the scientists.
- **Have students ask questions about what is interesting, puzzling, or important to find out (IPF questions).** Interesting observations students might make about the information in Figure 1 include the facts that it takes something special in a cell to cause it to migrate, cells are programmed to die to keep an organism in balance, and a mechanism exists for repairing damaged cells. Puzzling questions include: What causes some cells to be vulnerable to damage? What causes some people to be at higher risk for cancer than others? And, why are some parts of the body predestined as targets of metastasis? Important answers to find include factors that contribute to cell repair, how people can use research to improve their health, and what people can control to prevent cancer.
- **Pursue problem finding:** Embedded in the discussion of cancer are many problems students can unearth by probing the information more deeply for meaning, which IPF questioning initiates. Teachers can suggest varied problem finding strategies such as drawing a problem, asking a series of "why" questions to reveal possible causes of cancer, creating a flow map to sequentially link aspects of a situation, uncovering possible false assumptions about information, or minifying or magnifying a situation to understand its essence or scope.
- **Map problem finding and prioritize a problem:** Next, students organize problem finding results to show patterns and relationships among ideas. Again, teachers guide but do not make decisions for students. This process needs to be a construct of the learner, as illustrated by a cluster map the biology group creates. A map relating to Figure 1 helps students identify lifestyle factors and cancer as a problem to investigate and features such areas as cell behavior, genetics, the immune system, and cancer. The biology group draws arrows that connect various areas on their map to show how factors such as cell growth and the identification of aberrant cells by the immune system affect one another.



- **Investigate the problem:** To help the group strategize, teachers might ask: How will you organize your overall plan? And, what responsibilities will each group member have? Inquiry guiding questions might be: As you have decided to interview people, who will you interview? How will you find them? What information is needed? And, how will you record this?
- **Analyze results:** The responsibility for analyzing information lies with students. Guiding questions for the biology group might include: Would it be useful to compare people you interview for similarities or differences? How would you show this? In the process, teachers might also introduce students to basic data analysis methods.
- **Reiterate learning:** Reiteration is a distinguishing feature of PBL in which students present what they have learned to each other (Barrows, 1997). Biology students actively apply learning back to the problem to gain new understanding by reentering it from the beginning, critiquing and refining their original problem statement, thinking strategies, sources, and goals. They relate what

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they learned to other problems and try to extract concepts that have broad applicability. Metacognitive guiding questions might be: How do your results help you understand the problem you investigated? And, if you investigate this again, what would you do differently and why?

- **Generate solutions and recommendations:** Students need to revisit outcomes of the previous two steps to determine what direction to take. For example, after researching the scenario in Figure 1, biology students' data might point to prevention/intervention. Teachers can suggest idea-generating strategies such as asking "how?" each time a solution is proposed to clarify possible strategies and implementation steps, proposing improvements by substituting, combining, adapting or modifying ideas (Eberle, 1971), and using a metaphor to highlight aspects of a concept that might not ordinarily be perceived.
- **Communicate the results:** As stakeholders in a real situation, students need to communicate what they have learned. For example, biology students might consider creating a public information message emphasizing the relationship between certain lifestyle factors and cancer. Guiding questions might be: What general themes were discovered in our research? What conclusions can be reached? Who gains from this and how?
- **Conduct self-assessment:** Assessing one's performance progress is an important life skill that PBL develops. Students assess and share with the group their own problem finding, problem solving, knowledge acquisition, and self-directed and collaborative learning skills. Authentic assessment methods for which students develop discussion criteria include journal writing, lab notebooks, self-rating scales, peer interviews, and conferences with teachers. Teachers also provide their own assessments based on students' application of the 10-step model.

ENCOUNTERS OF THE RIGHT KIND

In science, answered questions lead to more questions. Understanding occurs in fits and starts, characterized by derailments, blind alleys, and shifts in focus. Problems change as they are being solved, resulting in constantly changing relationships between problems and solutions.

From the outset, PBL engages students in these important learning experiences. As illustrated, scientists' conversations about the challenges of their research is grist for launching student pursuits that replicate the process of science. Within the larger curriculum, this can be the basis for structuring a major piece of a learning agenda over an extended period of time, or for special study to enhance a part of a curriculum.

PBL gives students opportunities to be self-directed while maintaining cohesion in the classroom. It is effective with students of varying abilities because students choose the problems and methods of study based on development level and interests. Above all, says PBL expert Shelagh Gallagher (1995), PBL is a curricular and instructional approach that successfully resolves the seemingly contradictory demands of science education reform in a way that is true to the discipline of science, its process, and the larger goals of educating an independent reasoning citizenry. ✧

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