Introductory Physics: A Model Aproach

Biography: Robert Karplus

Robert Karplus was born in Vienna, Austria in 1927 where he grew up until 11 years of age. His mother, brother, and he left Vienna in March 1938 immediately after the German Anschluss. After a 6-month stay in Switzerland, the family emigrated to the United States and settled in the Boston area. He entered Harvard in 1943 (at the age of 16) as a freshman and by 1948 (at 21) had completed his Ph. D. His thesis under E. Bright Wilson was on microwave spectroscopy and included both experimental and theoretical work. He was early recognized for his brilliance, originality, energy, and cheerful, positive outlook.

After completing his Ph. D., Karplus worked at the Institute for Advanced Study in Princeton, where he became interested in the developing, but untested, theory of quantum electrodynamics (QED). The magnetic moment of the electron had been determined very precisely by means of a variety of experiments, but the best theoretical calculations of this important quantity (based on quantum mechanics but not QED) were seriously at variance with the experimental results. There was great interest among physicists in knowing whether or not a calculation based on QED would agree with the experimental results, but, because of the ambiguities and complexity of QED, no one had so far been able to do such a calculation.

Karplus, in collaboration with Norman Kroll, used QED to calculate the value of the magnetic moment of the electron. This was an extremely difficult calculation, requiring more than a year of intense effort from both men; the agreement between their result[1] and the experimental measurements was the first, dramatic confirmation of QED (for the development of which R. P. Feynman, J. Schwinger, and S. I. Tomonaga received the Nobel Prize).

Karplus continued his work at the highest level in theoretical physics for more than 10 years, at Harvard from 1950 to '54 and then at the University of California, Berkeley, publishing 50 research papers, mostly in QED but also in other areas of physics, including the Hall effect, Van Allen radiation, and cosmic rays. He is best known as a theorist, but he also thoroughly enjoyed experimental work, investigating the chemistry of Land camera instant pictures and setting up an experimental germanium purification assembly line for transistors. In 1958, Karplus was promoted to the rank of Professor at Berkeley, and he was compared favorably with other theorists his age, including T. D. Lee, M. Gell-Mann, and C. N. Yang.

In 1948 Karplus married Elizabeth Frazier, whom he had met at an international folk dance group he organized while at Harvard. They had seven children born between 1950 and 1962. Bob loved camping, hiking, exploring, and playing games with his family. When the oldest child, Beverly, was 7, Karplus accepted her invitation to present a science lesson on electricity to her second-grade class, using the Wimshurst machine he had inherited from his grandfather. Unfortunately, while the children enjoyed the demonstration, the lesson was a conceptual disaster. This stimulated Karplus to think about how to teach science better, and as the other children entered school he continued to visit their classes on a "show and tell" basis with various science experiments or demonstrations. Conversing with his children and their classmates, he became increasingly interested in children's learning, reasoning, and science concept development.

Central to Karplus' approach was a genuine interest and trust in others: he really believed that people were making sense - at least to themselves - and that it was a challenge to him to discover their reasoning, to uncover what they saw as important and what might be missing. A striking example of this is in a story recounted by his wife Elizabeth about a family outing exploring a mountain near their home. They found some fossil shells, and Karplus asked the children how the shells got up there. Rick, the youngest at 1½-2 years, immediately replied "the Sun," which baffled everyone.

Karplus, characteristically, was intrigued by this response, and he immediately invited Rick to explain his thinking. Rick responded that the Sun must have dried up all the water in the lake, leaving the shells! Of course, this ignores the fact that the shells were 3000 feet up on a steep hillside where no water could have stood long enough to be dried up. But Rick's explanation, as elicited by his father, shows an unsuspected depth of thought and a particularly imaginative way of accounting for at least some of the evidence. This short dialogue is a good example of how scientific thinking actually occurs, and it clearly opens the door to discussion and to further development of how to account for the presence of the shells.

Karplus didn't seem to find an illogical answer to be particularly disappointing or disturbing; on the contrary, it would pique his unquenchable curiosity. When he encountered a response that seemed off-target, he welcomed the opportunity to figure out a new puzzle, to discuss and "play" with the ideas once more, and to discover how someone else's mind worked.

Robert G. Fuller (p. 301) tells another characteristic story (corroborated by two different physicist co-workers) about how Karplus became interested in children's thinking:

> "Robert Karplus placed the toy truck in front of a child.
> He rolled the truck slowly across the desk.
> 'Did the truck move?' he asked.
> 'No.' replied the child.
> "(... He moved the truck back to its starting position. Again, he slowly rolled the toy truck across the desk to a new location.)

> 'Did the truck move?' he asked again.
> 'No.' the child replied once again.
> 'Can you explain to me why you say the truck did not move?' Karplus asked.
> '<u>It</u> did not move,' responded the child triumphantly, '<u>You</u> moved it.'
>
> "In that moment of puzzlement Robert Karplus was hooked. The physics that he knew and loved had not prepared him for such an experience. He discovered the importance of one's mental state in the shaping of learning and reasoning."

Fortunately, Karplus had the necessary blend of imagination, courage, intellect, and empathy needed to appreciate and meet this challenge. He pursued this new interest in science teaching and the psychology of reasoning with the same joy in the discovery of new knowledge with which he had pursued theoretical physics.

Within a few years, Karplus had changed careers - from theoretical physics, to research on science and math learning, and then to curriculum developer. Karplus quickly mastered what was already known about the development of thinking and reasoning, studying various psychologists, especially Piaget. Characteristically, Karplus also immediately began generating his own questions about children's thinking, collecting evidence, and developing his own interpretations and explanations of what he observed. This initial research was quite informal, using his own children. With his wife Elizabeth as a close collaborator, Karplus quickly progressed to the frontiers of what was then known about intellectual development, and he successfully engaged many other collaborators in further investigations.

This research was deceptive in its directness and apparent simplicity. Individuals were presented with carefully formulated problem situations, and *both* their responses *and* their explanations were recorded in some detail. This evidence was then analyzed, classified, and interpreted, using Piaget's stages of development as a general framework. The interpretations were quite provocative, often revealing unsuspected details about what the individuals understood and what they tended to neglect about the given problems. Karplus' insights into these matters were sufficiently detailed and profound that he can, in fact, be credited with the discovery of a variety of the conceptual processes that most people use in grappling with typical math and science problems.

Karplus also extended Piaget's theory to college students and adults; Piaget's theory included four stages, and Piaget had documented children's thinking in great detail, finding that most children made the transition from the 3rd stage (concrete operations) to the 4th stage (abstract reasoning) by about 16 years of age. Karplus, however, extended Piaget's methodology to older groups and found that many of these individuals had important gaps in their ability to use abstract reasoning in solving scientific, logical, and mathematical problems. Karplus further explored and documented the details of college students' and adults' thinking as they confronted the issues involved in this critical intellectual transition, finding that many of the issues and problems that he, Piaget, and others had discovered as critical for younger students were still relevant for older individuals, particularly when they were attempting to solve a problem in a discipline that was new to them.

Most science and math teachers, and researchers, had not previously been aware of these thinking patterns, partly because no one had really looked for them. To many teachers, such conceptual processes just seemed to be mistaken or to lead to "wrong" answers, and it seemed better not to dwell on such thinking, but rather to focus strictly on the "correct" reasoning so as to arrive at the "correct" answers.

Karplus, on the other hand, like Piaget, investigated the reasoning patterns that led to the "wrong" answers. He illuminated the pathways most people naturally tended to follow when they first encountered typical science and math problems. Karplus identified common conceptual misunderstandings, and he found that dealing directly with such issues often helped students to find more productive ways of thinking about science and math.

Karplus became an expert on Piaget's theory and a pioneer exponent of how to extend and apply it effectively in science teaching and curriculum development. He gave many, many talks about this throughout the country and beyond. Karplus wrote up his research results in an important series of collaborative papers: "Intellectual Development Beyond Elementary School I-VIII" (*School Science and Mathematics*, 1970-80). In cooperation with various others, Karplus also developed and presented a series of "Workshops on Physics Teaching and the Development of Reasoning" for college and high school physics teachers.

Karplus' new passion coincided, serendipitously, with the post-Sputnik wave of efforts to upgrade US science education. Beginning in the late 50s, many other scientists also devoted themselves to science education and the schools, but Karplus was from the start the leader at the elementary level.

Initially there was substantial reluctance at the National Science Foundation (NSF) to fund science curriculum projects at the elementary level, but this was overcome in 1959, when Karplus and three colleagues received the very first of many NSF grants for science course content improvement at the elementary level. This work evolved into a monumental, 15-year effort – the Science Curriculum Improvement Study (SCIS). Under the direction of Karplus and Herbert D. Thier, SCIS became a comprehensive, fully-tested, hands-on, laboratory-based program in both physical and biological science for grades K-6.

In addition to his work on K-6 science, Karplus regularly taught science courses at Berkeley, and I was his teaching assistant in 1968-70 in two of them. I watched Karplus perform in those situations, and he was simply terrific. He organized what he wanted to teach carefully and imaginatively, preparing thoroughly and keeping the needs and preconceptions of the students in mind. Karplus was a *wonderful* lecturer, articulating his ideas powerfully and clearly, explaining physics as simply as possible (but never pretending to make it, as Einstein was reputed to have said, simpler than that!), designing demonstrations that were both entertaining and on-target, inviting questions and answering them fully, preparing clearly-written, interesting homework assignments, using humor and connecting with current events, writing excellent exams, assigning grades that were both fair and defensible, and dealing promptly with student complaints and appeals.

Those were years of great turmoil at Berkeley, with the Vietnam War, politics, riots, tear gas, and police actions exerting tremendous pressure on everyone. Karplus was a steadying and calming presence throughout, never taking the easy way out (whether to the right or the left), helping students to figure out what was important, responding to students' concerns and interests, and constantly finding ways to keep the educational dialogue going.

I particularly remember how he went about planning Physics 10 (an introductory course for non-scientists), in which we were using the hardback edition of his textbook for the first time. We were assigned one of the traditional physics lab rooms, which had been regularly used in the past for Physics 10, and we had access to a very complete set of traditional physics apparatus. Karplus asked me to meet him in the lab, so we could, as he said, "cook up" some experiments for the semester. Within roughly 15 minutes "we" had reviewed the equipment and decided on the experiments, one of which was determining the wavelength of light by measuring the angle of the fringes produced by a diffraction grating. Needless to say, the speed and (relative) thoroughness with which "we" did this was quite impressive to my half of the team!

The lab had reasonably expensive spectroscopes, which are the standard instrument for measuring optical fringes from a diffraction grating. Karplus took one look at the beautiful spectroscopes and started taking them apart; he removed the telescope (which made it possible to measure angles extremely accurately), substituting a simple wooden sight, and he quickly simplified the apparatus to make it easier for the students to mount the gratings and to see how to actually go about measuring the angle of the fringes. Within a few minutes he had converted the needlessly complex spectroscopes into much simpler instruments which measured the angle to a lower, but still quite respectable, accuracy and which had a much higher educational payoff.

I clearly remember meeting the next day with Karplus and the other teaching assistant, John, a graduate student in theoretical physics who had previously assisted another professor with Physics 10. When Karplus mentioned the grating experiment, John remarked that the students would have great difficulty with the telescope. I will never forget John's amazed look when Karplus responded that he had eliminated this problem by getting rid of the telescope! John had measured the angle of optical fringes in his own undergraduate lab exercises to high accuracy with a telescope, and he had unconsciously assumed that this was how the measuirement always had to be done. It required an effort for him to realize the value of the trade-off of accuracy for speed and ease of understanding. As the course proceeded, John assimilated, from Karplus' behavior as much as from what he said, that the primary objective was to enable non-science students to carry out the experiments and think about physics on their own rather than to simply repeat the standard experiments and to memorize and apply the classic laws and principles. By the end of the course, John had become a much more adventurous, stimulating, and engaging teacher.

I also recall Karplus' creative solution to the problem of obtaining student feedback in the 600-student lecture hall where he often lectured. He distributed two cards to each student; the cards were colored with four different colors on the four faces. In the course of the lecture, Karplus would ask questions with four possible answers and ask students to show their responses by holding up their cards. He repeatedly demonstrated an uncanny capacity, given a certain pattern of colors, for coming up, "on the fly," with just the right additional example, question or problem to help hundreds of students figure out, right then and for themselves, where and how they were going wrong. It was a given at Berkeley: if Karplus was the teacher, whether there were 600 students, or 20, or 1, he would find a way to engage them all in thinking actively about physics.

I also completed my Ph. D. at Berkeley in 1972 under Karplus (in the Graduate Group in Science and Mathematics Education, which he and other faculty had founded). Thus I had many other chance to see Karplus in action, and, in particular, to see how he used what I came to think of as his "toolkit" for effective teaching. There were 4 items in this "toolkit":

1) The learning cycle of exploration, invention, and discovery,

2) The critical interplay between autonomy and input,

3) The importance of the conceptual structure of science. Karplus understood, in a very profound sense, the extent to which science, especially physics, can be molded and shaped. He considered science and physics to be plastic, malleable structures, with logical relationships that could be organized in many alternative ways. For Karplus, the first job of

a science teacher was to come up with an organized conceptual structure that would suit the audience and that would connect and relate together the key concepts and principles. This conceptual structure should, first of all, allow the instructor to begin the discussion with language and a set of concepts that are familiar at the appropriate level of abstraction. The instructor could then use operational and formal definitions, hands-on experiments, thought experiments, examples, and explanations, plus questions to and answers from the students, to build up the rest of the structure in a logical, understandable sequence.

4) A conception of teaching as a practical, only partially understood, yet improvable, activity, where the method for improvement lay in the collection and interpretation of detailed *evidence* about what the students had learned. This evidence, in Karplus' view, had to include *both* the right and wrong answers *and* the details of the explanations for the answers.

All of these ideas are explained clearly and in depth in Karplus' published papers (see the collection edited by Fuller, *A Love of Discovery*). However, in the literature, these ideas come across as relatively established principles, and one doesn't get a picture of how flexibly he used them and how powerful they were in his hands. Karplus actually employed these ideas not so much as laws or principles but as "heuristics," that is, as practical rules of thumb which one could exploit as necessary to help work out an effective solution for a given teaching situation.

In 1977 Karplus was elected as President of the American Association of Physics Teachers (AAPT), and in 1978 the National Science Teachers Association awarded him their Citation for Distinguished Service to Science Education. In 1980 he was awarded the AAPT's highest honor, the Oersted Medal, "for his many contributions to physics teaching at all levels and especially for his work in revealing the implications for physics teaching of research in the development of reasoning." (from the presentation by Dr. James Gerhart, Past President and Chair of the AAPT Awards Committee, Fuller, p. 228).

Unfortunately, in 1982 while jogging near Seattle, Washington, Karplus suffered a severe cardiac arrest, and after an eight-year illness he died in 1990. He is survived by his wife of 42 years, Elizabeth F. Karplus (teacher, co-author with Bob of many papers, graduate of Oberlin College in physics, and holder of Master's degrees from Wellesley in physics and from St. Mary's College in special education), as well as by his seven children and many grandchildren.

Karplus' intellectual legacy is monumental, especially in science education. His many published papers, curricula, and teaching materials form an impressive and continually useful resource (see Fuller). Even more important, in my opinion, was his inspirational example for an entire generation of science teachers, college faculty, scientists, and researchers. The level of Karplus' creativity and attention to detail, the depth of his understanding of physics and of students' thinking, as well as his rigor in collecting evidence coupled with his honesty in facing it provide a true standard of excellence in science education. Anyone who spent time with Karplus went away with unforgettable first-hand experience of how much fun it was to pursue good science teaching, how worthy of one's best efforts and how dynamic and interesting it could be.

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Note:

[1] R. Karplus and N. Kroll, "Fourth-Order Corrections in Quantum Electrodynamics and the Magnetic Moment of the Electron." 1950. *Phys. Rev.,* 77, 536-549. As usual in science, Karplus and Kroll's breakthrough wasn't quite as clear-cut at the time. Their original calculation using QED indeed agreed substantially better with the experimental results than previous calculations, but there was still a small discrepancy that they couldn't fully explain. A few years later, other theorists discovered that Karplus and Kroll had actually made a mistake in their calculations which was responsible for much of the remaining discrepancy. It is noteworthy that the line of inquiry pursued so productively by Karplus and Kroll is still active – theorists are still calculating, and experimentalists are still measuring, the value of the magnetic moment of the electron. Of course, there are newer theories than QED to test, the experiments and calculations are now done with the help of computers, and the accuracy is much higher, but the endeavor itself, as well as much of its style and shape, has grown from Karplus and Kroll's work of 1950.

Reference: Robert G. Fuller, Editor. *A Love of Discovery: Science Education, the Second Career of Robert Karplus*. (New York, Kluwer Academic/Plenum Publishers, 2002).

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