Remembering Bob

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In the summer of 1962, young Robert Dana Parmentier was finishing a master's thesis in the Department of Electrical Engineering at the University of Wisconsin, where it had been decided to support a major expansion of laboratory facilities in the rapidly developing area of solid state electronics. Jim Nordman and I—both spanking new PhDs—were put in charge of this effort, and we soon found ourselves involved in a variety of unfamiliar activities, including the slicing, polishing, cleaning, and doping of semiconductor crystals prior to the formation of *p-n* junctions by liquid and vapor phase epitaxy in addition to the more conventional process of dot alloying. We had much to learn, and welcomed Bob as a collaborator as he worked toward his doctorate in the area.

It was an exciting time, with research opportunities beckoning to us from several directions. From a more general perspective than had been originally contemplated by the Department, we began studying—both experimentally and theoretically—nonlinear electromagnetic wave propagation on semiconductor junctions with transverse dimensions large compared to a wave length. And there were many interesting nonlinear effects to consider.

Using ordinary reverse biased semiconductor diodes, the nonlinear capacitance of the junction causes shock waves, suggesting a means for generation of short pulses. At high doping levels, the junctions emit light to become semiconductor lasers, and at yet higher doping levels the negative conductance discovered by Leo Esaki appears, leading to a family of traveling wave amplifiers and oscillators. In 1966, this latter effect was also realized on insulating junctions between superconducting metals, rendered nonlinear through Ivar Giaever's tunneling of normal electrons.

As a basis for our theoretical work, we started with John Scott Russell's classic *Report on Waves*, a massive work that had been resting on a shelf of the University Library for well over a century, and in 1963 two events occurred that were to have decisive influences on Bob's professional life. The first of these was a Nobel Prize award to the British electrophysiologists Alan Hodgkin and Andrew Huxley for their masterful experimental, theoretical and numerical investigations of nonlinear wave propagation on a nerve fiber. This seminal work—to which applied mathematicians made no contributions whatsoever—pointed the way to Bob's doctoral research on the *neuristor*, a term recently coined for an electronic analog of a nerve axon.

The other event of 1963 was the experimental verification of Brian Josephson's prediction of tunneling by coupled electron pairs between superconducting metals, leading to an unusual sort of nonlinear inductor for which current is a periodic function of the magnetic flux. From this effect, the relevant nonlinear wave equation for transverse electromagnetic waves on a strip-line structure takes the form

$$\frac{\partial^2 \phi}{\partial x^2} - \frac{\partial^2 \phi}{\partial t^2} = \sin \phi \,, \tag{0.1}$$

where ϕ is a normalized measure of the magnetic flux trapped between the two superconducting strips.

Originally proposed in 1938 to describe dislocation dynamics in crystals and later to become widely known as the *sine-Gordon* equation, this is a nonlinear wave equation that conserves energy (which nerves and neuristors do not), and by the spring of 1966 we were aware that it carries little lumps of magnetic flux very much as Scott Russell's Great Wave of Translation transported lumps of water on the Union Canal near Edinburgh.

Just as Equation (0.1) can be viewed as a nonlinear augmentation of the standard wave equation, the system

$$\frac{\partial^2 u}{\partial x^2} - \frac{\partial u}{\partial t} = u(u-a)(u-1)\,, \tag{0.2}$$

is a nonlinear augmentation of the linear diffusion equation. Originally proposed in 1937 to describe the diffusion of genetic variations in spatially distributed populations, Equation (0.2) is the basic equation of excitable media, now known to have a variety of applications in chemistry and biology. Since it has a nonlinear traveling wave solution that represents the leading edge of a Hodgkin–Huxley nerve impulse, this equation is of central interest in the theory of a neuristor.

From a broader perspective, Equation (0.1) describes basic features of nonlinear wave propagation on *closed* (or energy conserving) systems, while Equation (0.2) plays the same role for *open* (or energy dissipating) systems; thus the two equations are fundamentally different and their traveling wave solutions have quite different behaviors. Equation (0.1) can be realized through Josephson tunneling and Equation (0.2) through both Esaki and Giaever tunneling. Interestingly, these three young researchers shared the Nobel Prize in physics in 1973.

Bob's doctoral research was concerned with both theoretical and experimental studies of these two equations, and his thesis was characterized by two unique features: it was entirely his own work and it was easily the shortest thesis that I have ever approved. Looking through *The Superconductive Tunnel Junction Neuristor* today, I am impressed by his simple and direct prose, and filled again with the delicious sense of how exciting was nonlinear science in those early days. So much was sitting just in front of us, waiting to be discovered.

This thesis was a tour de force, consisting of five distinct contributions.

- On the theoretical side, he introduced the idea of studying traveling wave stability in a moving frame, using this concept to establish the stability of step (or level changing) solutions of Equation (0.2).

- Again theoretically, he considered an augmentation of Equation (0.2) with a realistic description of superconducting surface impedance, leading to the hitherto unexpected possibility of a pulse-shaped traveling wave. The existence of such a solution is important if the superconducting transmission line is to be employed as a neuristor; a fact recognized in US Patent Number 3,717,773 "Neuristor transmission line for actively propagating pulses," which was awarded on February 20, 1973.
- On the experimental side of his research, Bob constructed an electronic transmission line model of the superconducting neuristor—using Esaki tunnel diodes—demonstrating that his neuristor does indeed have pulse-like solutions. Nowadays, this sort of check would be done on a digital computer, but in the 1960s electronic modeling was an effective, if tedious, approach.
- Extending fabrication procedures previously developed in our laboratory, he constructed tin–tin oxide–lead superconducting tunnel transmission lines of the Giaever type, showing that they could function as neuristors by propagating traveling pulses as predicted by his theory. This part of the research was a major effort, involving the making of 80 superconducting transmission lines, of which only 8 (all constructed during winter months when the air in the laboratory was very dry) were usable.
- Finally, Bob fabricated several superconducting transmission lines of the Josephson type—by reducing the thickness of the oxide layer—and showed that they could support pulse-like solutions of varying speeds, in agreement with the properties of Equation (0.1). These were the first such systems ever constructed.

All of this work was clearly presented in 94 double spaced pages—to which I do not recall making a single editorial correction—leading me to suspect (only half in jest) that the worth of a thesis is inversely proportional to its weight.

But it would be incorrect to leave the impression that Bob occupied himself only with scientific matters, for his social conscience was keenly developed. As the folly of the Vietnam War unfolded throughout the 1960s and the city of Madison became polarized into flocks of "hawks" and "doves," he was in the vanguard of Americans working for an end to the killing and a peaceful resolution of the conflict. Although those were difficult years for the University of Wisconsin, the activities of concerned and committed students like Bob showed it to be a truly great educational institution.

Having completed his thesis in September of 1967, he spent the 1967–68 academic year as a postdoctoral assistant in the Electronics Department of Professor Georg Bruun at the Technical University of Denmark, where a group was then engaged in a substantial program of neuristor research. It was during this period that Bob took the opportunity to visit Prague and share the euphoria of that beautiful city in its short-lived release from foreign domination, an experience that left a strong impression, deepening his suspicion of the motivations behind many official actions.

In the fall of 1968 Bob was recruited by Wisconsin's Electrical Engineering Department as a tenure track assistant professor, a signal honor for the department then had a firm policy against hiring its own graduates in order to avoid "inbreeding." The reasons for this departure from standard procedure was that integrated circuit technology was becoming an important aspect of solid state electronics, and both Jim Nordman and I were fully occupied with our own research activities. As the most competent person we knew, Bob was brought on board and charged with developing an integrated circuits laboratory.

Not surprisingly, he was also caught up by the general feeling of student unrest that characterized those days, eagerly embracing novel approaches to teaching that would supersede the dull habits of the past. Following his lead, we presented some courses together on the relationships between modern technology and national politics that attracted both graduate and undergraduate students from a wide spectrum of university departments. One such class, I recall, met by an evening campfire in a wooded park on Madison's Lake Mendota, where we would sit in a circle discussing philosophy, science, technology, and politics as the twilight deepened. The *circle* is important. Under Bob's inspiration, we were all students—the highest status of an academic—striving together to understand.

So two salient characteristics of Bob's nature become evident: a sure-footed and independent approach to his professional work, and a deeply rooted concern for the spiritual health of his society. But there was more.

Bob had a way of quietly influencing events, of deftly intervening at the critical moment without worrying about taking credit for the results. From Denmark in the spring of 1968, he wrote that I should look at the papers of one E R Caianiello, who was doing interesting work on the theory of the brain, a vast subject toward which Bob's neuristor studies beckoned. Upon being contacted, Professor Caianiello responded that he would be pleased to deliver some reprints in person, as he was soon to be visiting in Chicago. Over a lunch by the lake, I vividly recall, he sketched plans for the *Laboratorio di Cibernetica*, a new sort of research institution that was then being launched in the village of Arco Felice, near Naples.

Following ideas that had been advanced a decade before by the American mathematician Norbert Wiener, the *Laboratorio* staff would comprise mathematicians, physicists, engineers, chemists, computer scientists, electrophysiologists, and neurobiologists—working in a collaborative effort to understand the dynamic nature of a brain. As Wayne Johnson (who was just completing an experimental doctorate in superconductive devices) and I marveled at the scope of this scheme, Eduardo paused, looking thoughtfully at Wayne, and said: "I want you to come to Arco Felice and make Josephson junctions." In that moment, the Naples–Madison axis began.

Bob was the fourth Madisonian to trek to the *Laboratorio*, and the experience took hold of his psyche to an unanticipated degree. Encouraged by some subtle cultural chords, it seems, this Wisconsin boy felt immediately at home. There was something in the air of the *mezzogiorno* that resonated with deeper aspects of his spirit. Was it the haunting presence of Homer's "wine dark sea" or the glow of afternoon sunlight on Vesuvio's gorse? Or the exuberant dance of the olive trees in an autumn breeze, their silver underskirts flashing in the sun? Contributing perhaps to Bob's sense of belonging to Campania was the marvelous *cucina napoletana* and the fierce humor and independence of a people who have endured centuries of foreign domination. All of these reasons and more, I suspect, drew Bob into the bosom of Southern Italy.

Madison's loss was the gain of Naples as Bob carried his talent and experience in integrated circuit technology into this new environment, deftly wedding the new photo-lithographic fabrication techniques to emerging studies of nonlinear wave propagation on long Josephson junctions. Throughout the 1970s, theoretical, numerical and experimental research in the nonlinear science of Josephson transmission lines—described by physically motivated perturbations of the sine-Gordon equation—began to grow and prosper under the leadership of Bob and Antonio Barone and their students and colleagues, now far too many to list.

Although our personal and professional lives were entwined over more than three decades, Bob and I published very little together. One exception, of which I am particularly proud, was a paper that emerged from a famous soliton workshop that he organized in the summer of 1977 at the University of Salerno, to which he had moved a couple of years earlier. Held at the old quarters of the Physics Department in the middle of the city, this meeting attracted several stars of nonlinear science and provided unusual opportunities for real scientific and personal interactions. One formal talk in the morning was followed by lunch at a local restaurant that would have pleased Ernest Hemingway, lasting for a minimum of three hours and boasting unbounded conversation. Then in the late afternoon we would gather for another formal talk, after which smaller groups would carry on into the evening. It was from this inspired disorganization—perhaps only possible in the *mezzogiorno*—that it became clear how to solve Equation (0.1) with boundary conditions, making possible the analytic calculation of zero field steps in long (but finite) Josephson junctions.

In the mid-seventies, Bob's bent for subtly influencing events was exercised again. Having become friends with Niels Falsig Pedersen through meetings at international conferences, Bob encouraged the initiation of studies on Josephson junction solitons among physicists and applied mathematicians at DTU, anticipating the advantages that could be gained from a collaboration between those near the top and bottom (geographically speaking) of Europe. During the 1980s, as is evident from several chapters of this book, such research came of age. In the best traditions of nonlinear science, a remarkable *ménage à trois* of experimental, theoretical and numerical work emerged, relating the deep insights of soliton theory to a growing spectrum of experimental observations on long Josephson junctions. Reflecting the earlier Hodgkin-Huxley work on nerves, this international effort serves as a paradigm of how nonlinear science should be conducted.

Throughout these developments, Bob's steady influence was ever present, leading the group mind away from the abrasive competition that is all too common in many areas of modern science. Much of the civilized tone characterizing current investigations of superconductive devices stems from Bob's guiding hand.

Looking wistfully back over these fleeting years, I see a paradox in Bob's nature. Although ever tolerant of human foibles, sensitive to cultural imperatives, and ready to seek an intelligent compromise among conflicting personalities, he remained wary to the end of petty bureaucrats and mean spirited power games. Indeed, the last email messages we exchanged in December of 1996 were about codes for protecting internet users against prying officials of government.

Heading into the twenty-first century, practitioners of nonlinear science will miss Bob's wise and gentle counsel. While discussing his tragic death, Antonio Barone mentioned that in such cases, one often remarks that the departed person was a "good guy."

"But, you know," said Antonio, "Bob, he really *was* a good guy."

PREFACE

The world of science has seen many successes over the past century, but none has been more striking than the recent flowering of nonlinear research. Largely ignored in the realms of physics until some three decades ago, studies of the *emergence of coherent structures* from the underlying nonlinear dynamics is now a vital facet of applied and theoretical science, providing ample evidence—for those who still need it—that

The whole is more than the sum of its parts.

In this book, twenty-eight distinguished contributors describe these developments from the perspectives of their individual interests, paying particular attention to those aspects that seem to be of importance for the the coming century. Although the chapters included here comprise but a small portion of the current activities, we expect the readers to be impressed by its diversity and challenge.

The story opens with two fundamental chapters, underlying all of the others. The first of these presents a general description of *coherent phenomena* in a variety of experimental settings, including plasma physics, fluid dynamics and nonlinear optics. The second is a review of developments in *perturbation theory* that have been profoundly influenced by research in nonlinear science since the mid 1960s.

The next four chapters describe various studies of *Josephson junction superconductive devices,* which have both stimulated and been encouraged by corresponding developments in nonlinear science. Undreamed of 40 years ago, these devices have increased the sensitivities of magnetometers and voltmeters by several orders of magnitude, and they promise corresponding advances in submillimeter wave oscillators and in the speed of digital computations. Not unrelated to recent progress in the development of superconductors with higher operating temperatures are the quasi-two-dimensional magnets that support *vortex structures* as described in Chapter 7. This is an exciting field of theoretical study that stems directly from recent advances in condensed matter physics.

Without doubt, the most important technical application of the ubiquitous and hardy soliton is as a carrier of digital information along optical fibers. In recognition of this, five chapters are included on various aspects of modern optical research, ranging from general studies of basic properties to more detailed considerations of current design objectives. We believe these chapters will provide the reader with an unusually clear exposure to both the theoretical and the practical implications of *optical solitons* for the coming century.

Another significant branch of present day nonlinear science is that of *nonlinear lattices.* Going back to the early 1980s, this work is introducing the revolutionary concept of *local modes* into the study of molecular crystals. Of the six chapters in this area, the first deals with *dislocation dynamics* in crystals, and the second suggests the key role that two-dimensional *breathers* may have played in the formation of crystal structures, such as muscovite mica. Other chapters deal with novel phenomena arising from more than one length scale, mechanical models for lattice solitons, and the quantum theory of solitons in real lattices. From such work, we believe, may emerge basic elements for coherent information processing in the terahertz (far infra-red) region of the electromagnetic spectrum. The final chapter in this nonlinear lattice segment of the book describes ways in which "colored" thermal noise can give rise to *molecular motors* at the scale of nanometers. This idea has important implications for transport mechanisms that may operate within living cells, setting the stage for the final four chapters which address the *nonlinear science of life.*

Just as the past 100 years have been called the "century of physics," we expect that the next will be recognized as the "century of biology." Since almost every aspect of biology is nonlinear, this is the area in which we see the new ideas having their greatest impact. Thus the last four chapters are devoted to physical aspects of biological research.

The first of these describes various attempts to understand the dynamics of DNA in the context of modern biophysics. This survey provides the reader with a hierarchy of mathematical models, each gaining in accuracy as the computational difficulties correspondingly increase. Related to this chapter is the following one, describing exact numerical solutions for the dynamics of certain helical biomolecules that are components of natural protein.

The penultimate chapter—on exploratory investigations of the nonlinear dynamics of bacterial populations—is intended to draw physical scientists into the study of *life.* Similarly, the final chapter attempts to encourage young experimentalists and theorists to consider the most intricate dynamical system in the known universe: the *human brain.*

It is our hope that the readers of this book will make a significant contribution to research activities in the "century of biology."

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