Fundamental Theories of Physics 203

Gregg Jaeger · David Simon · Alexander V. Sergienko · Daniel Greenberger · Anton Zeilinger *Editors*

Quantum Arrangements

Contributions in Honor of Michael Horne

Springer

Fundamental Theories of Physics

Volume 203

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ISSN 0168-1222 ISSN 2365-6425 (electronic)
Fundamental Theories of Physics
ISBN 978-3-030-77366-3 ISBN 978-3-030-77367-0 (eBook)
https://doi.org/10.1007/978-3-030-77367-0

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Introduction

Mike Horne left his home of Mississippi after completing his college degree in 1975 and arrived in Boston to study physics, as a graduate student at Boston University under the supervision of the physicist-philosopher Abner Shimony who had himself recently arrived from MIT. He spent the rest of his life in Boston, buying a house in the Dorchester neighborhood of the city, teaching for over 45 years at nearby Stonehill College, and working with collaborators at Boston University, MIT, and in Vienna. He and his wife Carole, who worked for decades at the Harvard Book Store, became local fixtures, spending much of their spare time frequenting local restaurants, independent bookstores and theaters, and clubs where Mike often himself played in jazz groups where *musical* arrangements came into play, complementing the quantum mechanical arrangements considered during his research life. Indeed, in addition to his intellectual achievements, Mike was well known for his friendly nature and his kindness to friends, colleagues, students, and anyone else he happened to meet. He often spent much of his day sitting in the hall of the Stonehill Physics Department or in the atrium of the science building simply talking to anyone who was there about politics, music, history, physics, or anything else that crossed his mind. His students would often spend hours mesmerized by his stories about physics and its history. Dinners at Mike and Carole's house would always be remembered fondly by all participants for the excellent food, music, conversation, and warm and informal atmosphere.

This volume begins with a chapter by Carole Horne entitled "Remembering Mike." There, Carole discusses her life with Mike and recounts some of his more interesting interactions with friends and colleagues, providing a window into his unique personality and giving the reader an idea of why he will be so badly missed by all who knew him; of the recollections of Mike by his friends she writes, "If I made a word cloud of what I heard these are the words and phrases that would be in huge type: kind, gentle, modest, unpretentious, generous, curious, smart, funny, enthusiastic, passionate, a great storyteller, an inspiring teacher, a creative physicist and researcher." Carole emphasizes how much Mike loved to collaborate in all aspects of life and how he, much like Richard Feynman, enjoyed the hands-on approach to things by working with their parts, especially building them.

After Carole's illumination of the man and the character and a broad history of his physics collaborations and what he saw as its close connection to teaching, the reader next encounters a chapter filled with Mike's own words, now focused mainly on his work as a research physicist in his interview with the late Joan Bromberg and stored the American Institute of Physics' oral history of quantum physics of the Niels Bohr Library and Archives, in which he recollects first meeting his collaborators who quickly also became his friends, among whom are two of us editors of this volume (Anton Zeilinger and Daniel Greenberger) and contributors to it (John Clauser and Carole Horne) as well as his experiences as a graduate student of Abner at Boston University and a post-doctoral worker under Clifford Shull at MIT. The discussion of the interview centers in particular on Mike's work on Bell's theorem and quantum entanglement, which he referred to as simply "Bell physics." Neutron and photon physics research of collaborating research groups in Boston and Vienna was the realm of investigation, always with an eye in the end toward practical experimental tests, of which the "Clauser–Horne–Shimony–Holt" theorem became a towering mathematical result of 20th Century physics. In addition to describing how such results of his research came about, Mike also explains how he came to take his place as a professor of physics at Stonehill College, where he introduced a physics major for students pursuing bachelor's degrees and how the college was a perfect place for him to pursue his research.

One of Mike's major contributions to the foundations of modern physics, where physics meets philosophy, is the development, along with John Clauser, of the idea of "Clauser–Horne (CH) Local Realism." Roughly speaking, this is the idea that, in Mike's words, the world is made of "real stuff" that exists independent of any measurements and that obeys the causal rules imposed by special relativity. The "stuff" of CH Local Realism is a more precise version of what John Bell referred to as "beables" and Einstein, Podolsky, and Rosen called "elements of reality". Forty years of experiments testing the Clauser–Horne–Shimony–Holt (CHSH) inequality and other related Bell-type inequalities have shown unambiguously that CH Local Realism is violated. In his contribution to this volume, Clauser studies two formulations of quantum mechanics: The lab-space formulation, often used to study single-particle quantum mechanics, and the configuration-space version that is frequently employed in many-body quantum mechanics. He shows that these two formulations are inequivalent. This is in contradiction to the conclusion of Max Born, one of the earliest advocates of the lab-space formulation, who proclaimed them to be equivalent. Clauser concludes that lab-space formulations are untenable, as they do not correctly predict the expected violation of CH Local Realism.

Although the CHSH inequality has generally been used to tests the predictions of quantum theory with entangled photon states, another major component of Mike Horne's career involved the analysis of neutron diffraction experiments utilizing crystals. As always, Mike's interest was to use these experiments to shine light on fundamental aspects of quantum mechanics itself. Much of this work was done in collaboration with (future Nobel laureate) Shull and his students and other postdocs at MIT. Using the dynamical theory of diffraction, they looked at the effects of spin-orbit coupling in neutron–nucleus scattering and found a resonant enhancement of the spin-orbit scattering when an external magnetic field causes the Larmor precession distance to coincide with the Pendellösung distance in the crystal. Pendellösung is the periodic flow of energy between forward and backward Bragg scattering amplitudes in a crystal. Mike seems to have been the first to notice this enhancement, now known as the Neutron Spin-Pendellösung Resonance (NSPR) effect, and he derived the corresponding differential equations that describe the effect. Kenneth Finkelstein first discusses the theoretical description of NSPR and then describes an experiment that demonstrates the resonant enhancement effect and yields a precise value for the ratio of spin-orbit scattering to nuclear scattering in silicon. Those experimental results reveal a discrepancy with theoretical calculations. The physical principles underlying the required theoretical correction are then explored.

It has been pointed out by Mike's long-term colleague, friend, collaborator, and co-editor of our volume, Daniel "Danny" Greenberger, that Mike was always eager to reach the bottom of every physical effect and never be satisfied until he fully understood all the specific details and implications of them; Mike was always happy to share this understanding that often helped dispel some misconceptions in interpretation of quantum processes. One example of his scientific approach to complex physics topics is described in the next contribution here by Danny that deals with understanding multiple conceptual questions surrounding the Aharonov–Bohm effect. This piece offers an extremely clear and physically concise introduction to one of the effects most discussed over the last several decades in physics—the description is rigorous but sufficiently transparent to be understood by non-experts in that particular field as well as by philosophers of science.

The main issue discussed by Danny Greenberger in his chapter is how one could understand the non-classical nature of the Aharonov–Bohm effect and explain the modulation of electron's phases while there is no real magnetic field present in a space outside the solenoid. He points out a very original contribution of Mike Horne to the study of the AB Effect that offers an interesting interpretation dealing with the need to set up initial experimental conditions by using real fields and forces prior to conducting the final experiment with stationary magnetic fields inside and outside the solenoid. This concept—that of taking into consideration all energy-related parameters contributing to the quantum system under a considered preparation—has significant implications and helps to understand the nature of many conceptual paradoxes surrounding quantum mechanical effects.

The general notion and specific features of quantum entanglement—the implications of which Mike and his collaborators have pioneered—have been at the heart of many quantum mechanical and, more recently, quantum information processing effects that have occupied the minds of researchers and philosophers now for a half-century. The multiple manners of quantifying entanglement that can be found in specific physical systems, as well as elaborate schemes for their observation that have been developed have been impacted by their work. These scientific and intellectual challenges were the perennial subject of Mike's research, and the fruits of his unique approach to doing physics left significant impact on this field by actively participating in the construction of two major Bell's inequalities that have been widely used in the field.

Mike Horne's enthusiasm and dedication to resolving such complex issues relating to entanglement are also highlighted in personal recollection by Anton Zeilinger, Marek Zukowski, and Caslav Brukner which follows. The use of information as an indicator and the connection between quantum systems or between parts of a single complex quantum system is one of the most intuitive and informative approaches to understanding entanglement. Many specific details of this useful and informative concept are discussed in great detail in this chapter by these three major experts in the field. One of the central outcomes of this contribution is the demonstration of the universality of their approach which is exhibited through the equivalence between two entanglement evaluation approaches based on the information theoretic and Bell's inequalities formalisms.

Herbert Bernstein's contribution to this demonstrates Mike Horne's interest in photon physics and in collaboration, particularly his joint work with Cliff Shull, Anton Zeilinger, and Danny Greenberger. They all sought to answer the question "*Why* the quantum?" by another great of the field, John Archibald Wheeler. Bernstein's contribution is an experiment aimed at providing evidence that each individual particle can be described by a corresponding state, that is, wavefunction that would distinguish its state from a statistical state. The experiment invokes the technique of heralded single-photon detection. A key technique of the experiment is to create "signal" photons by parametric down-conversion in pairs, one of which, the idler, heralds the presence of the corresponding signal photon to the experimental apparatus. The signal photons are prepared in different states so that no individual-system state appears is prepared more than once in the entire set of preparations. The set of individual single-particle measurements resulting is then to be compared with the predications of standard quantum mechanics. The observable property at the center of the experiment is that of the polarization degree of freedom: For the linear polarization preparations, this treatment demonstrates that the cosine-squared Law of Malus is confirmed by preparing the individual systems in all a full set of differing orientations and measuring the passage of the systems through a polarization analyzer of fixed orientation.

The work of Mike Horne was always aimed at either a better understanding the fundamental elements of quantum mechanics or the surprising implications of those fundamental elements. One of the most unique aspects of the foundations of quantum mechanics as physics has come to grips with them has been the physics of measurement. Don Howard's contribution to this volume considers the various means by which the measurement problem of quantum mechanics, the problem that the modeling of measurement by the linear state evolution of the Schrödinger equation alone, predicts indefinite outcomes of measurement when the measuring device is part of the system studied. In particular, Howard suggests taking this physical law seriously to see whether the appearance of definite measurement outcomes could be an illusion brought about by quantum state decoherence. He notes that the name applied to the study of this sort of behavior, *decoherence theory*, is a confusing one in that it suggests that so-called state collapse is what takes place under this phenomenon whereas quite the opposite is true: Coherence is retained in composite systems but relates to what can be measured in a far subtler way than is present, for example, when one has a simple coherent wave-packet as the spatial representation of a non-composite system. Howard explores question of what sort of "observational indistinguishability" of states corresponding to different measurement outcomes amounts to, which he identifies as a puzzle to be solved. This analysis begins with the reconsideration of the notion of complementarity in the thought of Niels Bohr and the understanding of entanglement before Erwin Schrödinger's naming of it first lurked in the minds of Bohr, Albert Einstein, Boris Podolsky, and Nathaniel Rosen who together made the notion of physical realism one that has been directly pursued for nearly a century.

To set the stage for understanding this notion both physically and philosophically, Howard lays out the history of thinking about entanglement in the late 1920s and early 1930s and the evidence of its commonplace consideration. He notes that Einstein considered in relation to the statistics of multi-particle systems, Bose vs. Boltzmann statistics, in particular. Other examples, in writings of Hermann Weyl and Wolfgang Pauli are also noted. Howard then takes up the question of the relation between entanglement and complementarity, that entanglement entails complementarity, at least in Bohr's own sense of the notion. Another important aspect of the consideration of the foundations of quantum theory is the distinction between the classical and the non-classical, which is connected in the physics of that era with the appearance of measurement outcomes, most often understood capable of appearing in measuring systems that, at least when alone, are well modeled by classical physics. Howard carefully considers those characteristics commonly attributed to possible measuring instruments, such as mass, size, and number of degrees of freedom, and critically so. This, together with Bohr's notion of a "phenomenon," is then assembled into a unified picture of Bohr's conception of what takes place in the measurement of a quantum system.

Such a picture of physics allowed Bohr to advance the thesis that quantum and classical physical descriptions can be essentially equivalent. Howard illustrates this via the consideration of context-dependent mixtures, to be distinguished from improper mixtures represented by reduced density matrices. They are, rather, joint density matrices representing proper mixtures that "can be interpreted as if they represented, *with respect to the degrees of freedom measurable in the stipulated context and only those degrees of freedom*, mutually independent systems." In that respect, they correspond to what Bohr regarded as classical descriptions.

All of the above enables Howard to present a dissolution of the measurement problem along the above lines: "Applying linear, Schrödinger dynamics to the system-instrument-environment interaction drives the joint, system-instrument-environment state into an entangled, pure, joint state that is observationally indistinguishable from the relevant context-dependent mixture picked out by the measurement context because the pure, joint state and that mixture over joint eigenstates picked out by the measurement context give exactly the same statistical predictions for all observables measurable in that context." What is offered is a mathematical equivalence, not simply some imprecise suggestion of one. Thus, finally, he argues that environment-induced decoherence "was, all along, the real point toward which Bohr was gesturing with the doctrines of complementarity and classical concepts."

Another issue to emerge in the history of quantum physics that owes much to Bohr is complementarity. And, not surprisingly, Mike Horne and his collaborators (including two of the editors of this volume, Gregg Jaeger, Mike's former thesis-advisor Abner Shimony, and Anton Zeilinger) also probed the complementarity between single-particle interference, for which some offer more classical explanations, and quantum entangled-state *multi-particle interference*, which has no adequate classical explanation. Quantum interference had been at the focus of extensive theoretical and experimental investigation for years, but these workers were expanding this consideration to systems of their complementarity as well as the consideration of the joint interference of more than two quantum particles. The nature of such higher-order interferences and associated complementarities remains an area of active research. Mike's scientific curiosity and interest in solving challenging problems homed in on this topic quickly; his vision of the problem and the essence of this exciting quantum physical challenge are presented with careful attention to detail by Christoph Daniel and Gregor Weihs in their contribution here. While previous work in this area has focused on the effect of local state transformations on multi-particle states, the contribution of Daniel and Weihs examines the effect of global transformations, showing that the complementarity rules derived by Mike Horne and collaborators naturally extend to this case when the role of quantum entanglement is properly accounted for. They also note, in light of their new results as well as Mike's own, that his personal goal of a three-body complementarity relation involving single particle, two particles, and three particles that any such three-body complementarity relation would preferably be addressed in terms of entanglement between the constituents rather than ordinary interference visibilities.

Another of the significant theoretical results Mike Horne produced in his collaborations is the Greenberger–Horne–Zeilinger (GHZ) theorem, which involves the consideration of quantum states of a four-qubit system. They already mentioned that the same results would hold for three-qubit systems. The broader context is that of values (plus or minus one) that can be assigned by any putative non-contextual hidden-variables model for quantum mechanics. Later, David Mermin considered such a set of observables in the context of the three-qubit system. The GHZ theorem is based on the consideration of quantum state vectors—now widely used and called "GHZ states"—in which the values of the quantities involved are correlated in the particular ways the significance of which was first pointed out by this trio. In the final contribution to this volume, Mordecai Waegell and P. K. Aravind explore logical relations between propositions in quantum theory by relating the original result of GHZ to David Mermin's different proof of their result, one of the Kochen–Specker theorems based on the ten GHZ observables. These quantities can be arranged elegantly along the edges of a pentagram with values assigned to the observables being plus or minus one that can be viewed as an edge-coloring problem.

Mermin showed how the correlation requirements imposed on these values preclude a logically consistent assignment of values "at once" to all these quantities. Waegell and Aravind demonstrate how this proof can be transmuted into a different one for the same result, that of Kernaghan and Peres, based on the eigenstates of those observables. The Kernaghan–Peres result was arrived at by returning again to the consideration of quantum state vectors, with the price, again, of a slight loss of simplicity. This shift of approach is possible because these proofs are essentially "parity proofs," that is, ones based on an even–odd contradiction. Waegell and Aravind show that the transformation of perspectives, which they called a "looking glass" relation, has proven valuable in understanding other aspects of quantum theory in the last thirty years.

This volume in honor of Mike Horne offers not only many fond recollections of Mike as a person and documents important aspects of his work as a scientist, but also gathers some of the most recent work that shows that his impact on his collaborators and physics at large continues.

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Chapter 1
Remembering Mike

Carole Horne

When Mike died I heard from many, many people who knew him—friends, fellow physicists, fellow faculty members, students, musicians – and I've heard from many more since. I've gotten used to meeting people—neighbors, people in stores and restaurants, electricians, and mail carriers—who have stories about the ways in which Mike affected their lives. If I made a word cloud of what I heard, these are the words and phrases that would be in huge type: kind, gentle, modest, unpretentious, generous, curious, smart, funny, enthusiastic, passionate, a great storyteller, an inspiring teacher, a creative physicist and researcher. Readers who knew him will recognize Mike in these recollections, I think.

I'd like to write about those qualities that, for me, get to the heart of who Mike was. First and foremost, he was the most joyful person I've ever known. He was full of wonder at existence, excited and fascinated by the world and what we can understand of it. Many mornings, lying in bed, he'd wake up, wake me up, and as we shook off our sleepiness would say with a little smile, "Ain't life grand?" And he often said, apropos of nothing in particular, "Isn't it great to be alive." He actually did say those things. He was quite aware of, and outraged by, all the things wrong with the world, but nevertheless he felt that the two of us were extraordinarily lucky. I've never known anybody else like that. Many people who wrote to me said things like "his love of life was contagious, his joy infectious." And it was. He threw himself wholeheartedly into the many things he loved.

And then there was Mike's impulse to share everything he loved or discovered. It was most obvious in his physics. He loved to collaborate. From his early grad school days in the basement office he shared with ten or so other students, he was happiest when they all talked about what they were working on, critiquing each other's ideas, adding to each other's efforts, cheering each other on when someone

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© Springer Nature Switzerland AG 2021
G. Jaeger et al. (eds.), *Quantum Arrangements*, Fundamental Theories of Physics 203,
https://doi.org/10.1007/978-3-030-77367-0_1

had a breakthrough. His earliest successes as a physicist were in collaboration with his dissertation advisor at Boston University, Abner Shimony, and John Clauser, and Richard Holt. He and Abner continued to collaborate long after Mike received his doctorate. Later, his collaborations with Danny Greenberger, Anton Zeilinger, Cliff Shull and others—which started in Cliff Shull's lab at MIT—lasted his whole career.

But the impulse to share and collaborate went beyond his physics. More than many couples, we shared most everything we did—music, cooking, traveling, hosting people at our house—and told each other about everything we encountered that excited us. Mike shared things with everyone. When he discovered a new movie, especially a classic movie from the 40s or 50s, he tried to convince everybody to watch it. When we successfully tried a new dish, he'd spread the recipe around. When he read something that he was especially impressed by, he'd make copies to carry around and pass out. If he discovered a new jazz musician or recording, there were any number of people who would hear about it. He played music with people as often as he could, and after all, what is jazz improvisation but a deep collaboration? And something new in physics? Everybody heard about it. When gravitational waves were detected at LIGO, he didn't stop telling people for weeks.

About his modesty, which virtually everyone mentions. More than most people, I think, Mike didn't worry much about what other people thought of him. In his career he wasn't ambitious in the usual sense; he simply wanted to understand things, and was happy and proud when he'd figured out something that he thought was important. Although he was recognized as a special teacher, he didn't think of his teaching as a way to advancement, but as a way to share with students a new view of the world. He didn't do things for the acclaim, although he appreciated it (in his low-key way) when it came. He had a very balanced and unassuming sense of himself, happy and confident, but not overly impressed with himself either. A relative of mine, who thought she'd be intimidated by someone with a Ph.D., once said she liked being around Mike because "he's just a regular person." I suspect this modesty was why children and young people were so drawn to him. A nephew wrote to me about Mike being the first adult who didn't talk down to him, and who listened to him seriously. He said he tries to do that with his own students now that he's a teacher.

Mike's attitude toward physics was unusual. He was passionate about it, but he came to it from books he read as a junior in high school. NSF had commissioned a series of science books, published by Doubleday Anchor, which included biographies of great physicists and stories about foundational discoveries in science. He always said he was more affected by the sense of what it meant to do physics—the excitement and human drama of the endeavor—than he was by the textbooks he studied. He once wrote "the physicist, when asked 'what is physics anyway, and why do you do it?' will talk about beauty, elegance, mystery, excitement, reality, humility, goose bumps, and tears." He was interested in the history and philosophy of science, and applied only to Boston University for grad school because he could study both physics and its history. In 1968, when Abner Shimony came to BU from MIT, he became Mike's dissertation advisor. What a lucky happenstance! Being both a physicist and a philosopher, Abner's interests were exactly right for Mike. At a time when mainstream physics was not much interested in foundations of physics, Mike was fascinated. It didn't matter to him—in fact, I doubt he ever thought about it—that his dissertation topic might not be a smart career move. Eventually though, the work he and Abner did helped to bring about a wide appreciation of nonlocality and entanglement as physics worth studying.

When he came home in 1976 from an early conference organized by John Bell in Erice, called Experimental Quantum Mechanics, I remember Mike's excitement telling me about having met this young Austrian physicist, Anton Zeilinger. They had apparently hit it off, staying up very late in the evenings, drinking wine and talking about foundations of quantum mechanics. Mike felt that he'd met someone who shared some of his thinking about physics, and he was thrilled when Anton came for the year as a postdoc to Cliff Shull's lab where Mike was on sabbatical from Stonehill College as a visiting scientist. Danny Greenberger first met Mike and Anton at a conference in Grenoble in 1978. They hit it off wonderfully too, and Danny started coming up from New York to Cliff's lab at MIT. The GHZ collaboration went on for 40 years. There were many conferences, including in Japan, Vienna, and New York (where I was a tag-along and got to experience the physics world Mike lived in, which became an important part of my life too). Perhaps the best conference, though, was in Amherst in April of 1990. There were no prepared talks, no schedule, no proceedings, just conversations. Mike thought it was the perfect idea for a meeting. There were a small number of people attending, including John and Mary Bell. Danny, Mike, and Anton talked about the GHZ theorem, which was new, and they were excited by Bell's interest. Sadly, Bell died unexpectedly that October.

Mike strongly believed that simplicity was the essence of physics; it's one of the things that drew him to the field. He started every semester by telling his students "if it's complicated it's not physics". Mike believed that teaching physics made him think about physics in simpler, clearer ways. He thought that if you couldn't explain something to someone with no physics background, without watering it down, you didn't really understand it yourself. It didn't matter whether he was talking to students or to fellow physicists, he wanted simple, elegant explanations. He was an unusually visual person, and I think that helped him see things more simply. A funny aside—there's a famous photo that has a cow in it, but the way it's taken you see an abstract photo, and don't see the cow. When I showed it to him and asked what he saw, he said "you mean besides the cow?" As a physics colleague related to me, "topological things seemed so natural coming from him. He was always explaining things in simple, uncluttered ways to all of us."

Mike was a dedicated teacher. Because not every student found physics simple to learn, he spent his time at the college not in his office but in the Atrium, available for any student to come get extra help. He often talked with his students about his love of physics, and his view that questions arise in physics not for practical reasons but "only if you want to understand." Just as he thought that teaching physics made him a better physicist, he thought that doing physics was essential to being a good teacher.

Doing physics and teaching physics were inextricably connected for Mike. For example, from his dissertation topic to the end of his career, although he was a theorist, he straddled the border, trying to devise doable experimental tests of existing theory.

He sometimes called this "quantum archeology," a phrase that Abner loved. His involvement with experiments transferred to his teaching. When he was beginning his teaching career, he wanted to develop a lab course in which students measured the fundamental constants using the original techniques. Unable to buy commercial versions of all the equipment, some theorists might have abandoned the idea. Because he thought exposure to these original experiments was so important, he learned how and built most of it himself.

Education, Mike thought, especially science education, could change your life. When Stonehill proposed dropping the general studies requirement from two courses to one, he wrote an argument against the change; he titled it (after a John McPhee book) "A Sense of Where You Are," and he spread it around campus. He told a story about going to college and eagerly signing up for three classes—history of science, astronomy, and physical anthropology. He said those courses gave him a new way of thinking about the world and our place in it. A few years ago he wrote, "To this day when I step outside in the morning, my inner voice often says something like 'I'm a recent hominid and I can do physics.' The tone of that inner voice is that of the Truman Capote character in the film *To Kill a Mockingbird*, who introduced himself with 'I'm seven and I can read'." That's what he wanted for his students.

Mike was thoroughly captivated by physics, especially the foundations. He thought that doing physics was a creative endeavor, in the same way that art and music are creative. He completely rejected the idea of physics as a dry, boring, difficult subject. He was so involved in whatever physics he was currently working on that when an idea came to him, he'd interrupt what he was doing to capture it. A friend reminded me of seeing Mike at a party, sitting in the corner, writing something down in a notebook. At the college, when he wasn't talking to students, he was doing physics with the pencil and notebook he always had with him.

Mike brought that kind of passion to his other loves: jazz, building things, politics, movies, cooking. A recent book, *The Quantum Dissidents: Rebuilding the Foundations of Quantum Mechanics (1950–1990)*, by Olival Freire, Jr., suggests that there may be a connection between the political activism of the mid-to-late twentieth century and the concurrent questioning of the foundations of physics. It's possible. For as long as I knew him, Mike had a deep belief in progressive politics. He talked about how his dad, born in 1896 in rural Mississippi, ran in the mid 30s for county school superintendent, and having won, promptly built a school for Black kids, who had not had a school until then. Equally promptly, burning crosses appeared in the front yard, and his dad wasn't re-elected. Although Mike wasn't born for another decade, he was profoundly affected by that story. He was a college sophomore and I was a freshman in 1962, when we met at the University of Mississippi the fall that James Meredith enrolled and became the first African American student to attend the university. Meredith was accompanied by U.S. Marshals and his arrival was met with several thousand people rioting, driving around the campus waving Confederate flags, shooting guns, burning cars. Two men were killed and National Guard troops were sent and remained on campus for the school year. This experience solidified for both of us our commitment to civil rights, to racial justice and equality, and to progressive politics. When Mike graduated in 1965, we married and moved to Boston for Mike to start graduate school. We never returned to live in the south.

Lots of people have talked about Mike's love of jazz, both playing it and listening to it. He thought jazz, like physics, could change your life, and as with physics, he wanted to tell everyone about it. As with physics, his gift was being able to explain musical things simply to people untrained in music: time, space, playing ahead of or behind the beat, minor keys, the way musicians listen to each other, they way they "talk" with their instruments. He could make you hear with bigger ears, make you understand in a deeper way. One of the best descriptions I have is from a relative who once picked up Mike's upright bass and tried to play along with the record that was on. At one point a series of notes sounded right, and Mike called from another room, "You got it!". "No Mike," he later wrote, "I didn't get it, you gave it to me."

Building things was another love of Mike's. From the oversized dining room table he built the first year we bought our house, using tools from the shop in the BU physics department, to bookcases all over the house, to the enormous project of rebuilding the carriage barn behind our house, there was always a building project underway. The carriage barn, built in 1874, had been moved from its original location to nearer the house, and had fallen off the badly-built new foundation. Restoring it was a project that took Mike and my brother, Larry, five summers, and entailed lifting the whole structure on specially made steel posts that he designed and had built, and building a new foundation. He was enormously proud of it when it was done. In 2015 we threw a party in the barn, complete with a whole roasted pig, to celebrate our 50th wedding anniversary and 140 years of the barn.

At its heart, the story of Mike's life is a love story. Boy falls in love with music at a young age. Boy meets girl, falls in love and marries. Boy discovers physics and teaching, falls in love and spends his life doing them, has a life rich with loving friendships. Like every human story, there's a sad ending, although Mike would disagree with that description. But like some human stories there's a lasting impact. Mike's enthusiasm for all the things he loved was boundless. As a colleague wrote, "maybe that was the key to his rich and multifaceted life: he was always up for having second helpings; he was on for another set." And he was always teaching—often by example—mostly how to live (Figs. 1.1, 1.2, 1.3 and 1.4).

A note on the players

There are so many people who made Mike's career a joy. I've talked about Abner Shimony, Mike's dissertation advisor, who grew up in Memphis and became a life-long collaborator. Mike's dissertation topic was completed simultaneously by John Clauser at Columbia, and Clauser agreed to collaborate on the publication with Mike, Abner, and Dick Holt. Holt was the graduate student at Harvard who planned to do the proposed experiment, the experimental test of the CHSH-Bell's theorem predictions. Mike and John went on to collaborate on several papers, most notably leading to the 1974 Clauser–Horne (CH) inequality.

When Mike decided to apply only to BU for grad school, it was because he knew that the physics department chair, Robert Cohen, was a co-founder of the Center for the Philosophy and History of Science, and its Boston Colloquium for Philosophy of

Fig. 1.1 Abner Shimony, Mike, and Anton Zeilinger

Science. The Center was founded by Bob and Marx Wartofsky in 1960 as an offshoot of the Institute for the Unity of Science, which was itself the American transplant of the historic Vienna Circle. So things came full circle in Mike's physics life, with connections to Vienna. Bob Cohen was important in two other ways: he helped, with Chuck Willis, convince Abner to come from MIT to BU, and he told Mike about an available job at Stonehill College.

In 1970, Chet Raymo, another southerner, and an accomplished naturalist and writer, hired Mike to teach the physics classes at Stonehill College, the perfect job for him: a small college where there was no pressure to publish for the sake of advancement, near Boston where he could work with other physicists. Mike always gave Chet credit for teaching him many things about good teaching.

Mike showed up unannounced at MIT in Cliff Shull's lab in 1976 to talk about a possible experiment for Shull's new neutron interferometer, and after talking a while

Fig. 1.2 Danny Greenberger, Mike, and Anton Zeilinger (GHZ)

Fig. 1.3 Group photo in Shull's lab (circa 1982?)—left to right, John Arthur, Anton Zeilinger, Cliff Shull, Mike Horne, Danny Greenberger, Ken Finkelstein, and Tony Klein

Fig. 1.4 Mike and Carole Horne

asked “Can I play?” Cliff gestured to an empty desk and said “Why don’t you sit there.” Mike worked in the lab in all his free time for almost fifteen years. Danny Greenberger started coming to the lab in 1978, and Herb Bernstein from Hampshire College was in the lab as a visitor too. In Cliff’s lab, Mike worked with a number of students: Ken Finkelstein, Don Atwood, John Arthur, Steve Collins, and Dan Gilden among them. Joe Callerame was a postdoc in the lab, working on building the interferometer. Tony Klein from Melbourne, Australia was also there on several extended visits.

After Shull retired in 1986, Mike, Danny, Herb, and Anton applied for NSF grants that continued for about four years. Cliff continued to visit and to look over the shoulders of students doing experiments in what he called the “remnants of my old research laboratory.”

After that, Mike made many trips to Austria to Anton’s lab, where he met and worked with a number of students, postdocs, and physicists over the years, most notably Marek Zukowski from the University of Gdansk. He loved working with the students, and always returned with a new idea to think about.

There were physicists that Mike had many conversations with, especially Helmut Rauch, Anton’s advisor in Vienna, Sam Werner at the University of Missouri, and Yanhue Shih at Maryland. He also at one point started visiting David Pritchard’s lab at MIT.