BIOGRAPHICAL MEMOIRS

Toichiro Kinoshita

January 23, 1925–March 23, 2023
Elected to the NAS, 1991

A Biographical Memoir by Robert P. Crease and Makiko Nio

Toichiro "Tom" Kinoshita was a path-breaking theoretical physicist who helped turn quantum electrodynamics (QED), the theory of high-energy particle physics, into the most precise theory in human thought. Over his career—three-quarters of a century long—he acquired recognition as a master of the fundamentals of QED and was regarded as an invaluable resource by high-energy physicists who worked in any of its areas. In particular, Kinoshita was known for working out the precise value of a number known as *g*-2, which could be computed from the foundations of QED. Because *g*-2 could also be measured with extreme accuracy, the difference between Kinoshita's value and the experimental one was often regarded as the most important indication of the comprehensiveness and soundness of the theory; the high-energy world held its breath at every new opportunity for comparison. Kinoshita was born in Japan and entered graduate school in Tokyo during World War II, shortly before Allied bombing began to reduce much of the city to rubble. After securing a visa to the United States, he worked at the Institute for Advanced Study in Princeton, New Jersey, at Columbia University, and at Cornell University, where he spent the majority of his career. He thought about physics all the time and worked nonstop. Kinoshita was quiet and reserved, with a prodigious ability to concentrate, observe, analyze, and mentally store information, all traits that he needed to carry off one of the greatest feats of calculation in science.

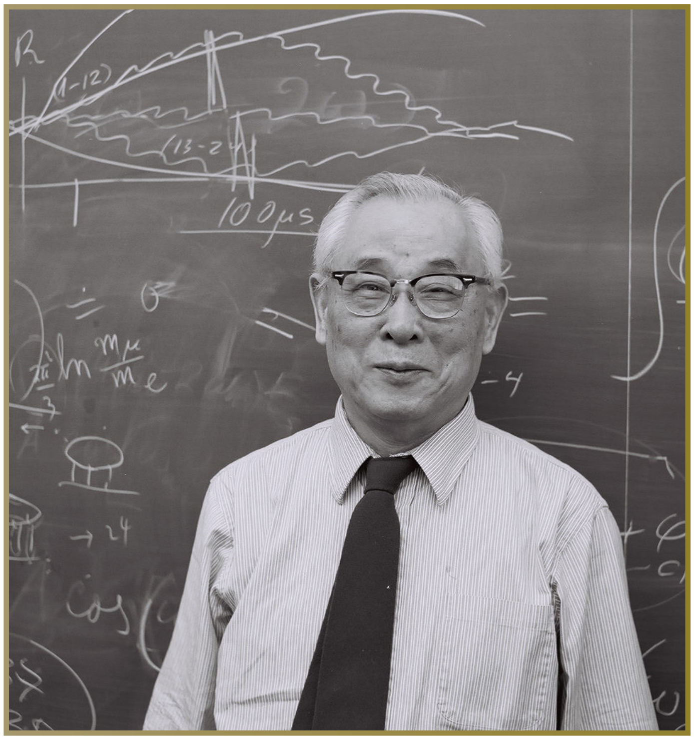

Figure 1 Headshot against blackboard.

Early Life and Education

Kinoshita was born on January 23, 1925, in Yonago, a small coastal city in Western Honshu, Japan, to a family of farmers who owned rice fields worked by laborers. He was expected to inherit the family business, but his interests diverged early. In elementary school, he read books about Thomas Edison and Guglielmo Marconi, which made him want to become a scientist. While walking to his secondary school four kilometers away, he would pass a bookstore from which he emerged with Japanese translations of the Einstein-Infeld textbook on relativity and Louis de Broglie's on quantum mechanics. He took a test to see if he could enter Ichiko, a dai-ichi or First Higher School, Japan's premiere high school and connected with the University of Tokyo. He did not pass the test. Eight decades later, he could still remember the math problem that he missed and when asked could write out the problem, its solution, and how he had gone wrong. The second time he took the test, he was well prepared. He came in at the top and entered.

Kinoshita graduated from Ichiko in 1944. That September, he enrolled as a student in the University of Tokyo, known as Todai. He was thoroughly entranced by physics, and the familial obligation began to weigh on him. By then the military was short on soldiers, and students were drafted. Its student population declining, Todai had to condense and accelerate its curriculum. By this time, American bombing of Tokyo had begun, and though Todai was spared because it was not near military targets, periodic air raids required students and faculty to stop everything and scurry to shelters. Physics students fared better than others, for they were often sent to military labs. Kinoshita was not drafted the first time around, perhaps because he was a physics student, but had reasons to fear that he would soon be drafted anyway and sent to the front, an increasingly likely—and deadly—prospect.

Kinoshita took all Todai's required first-year courses that fall and all the second year's courses in the spring. By the summer of 1945, he had finished his formal training, which had taken him a year and a half. That summer, while visiting his family in Yonago, he heard the news that Hiroshima, about eighty miles to the south, had been flattened. Kinoshita realized that it could not be an ordinary bomb and thought immediately that it had to be one tapping atomic energy. He returned to Tokyo right afterwards, and while at the Shinjuku train station he heard Emperor Hirohito on the public address system—which was unprecedented—announcing Japan's surrender. Kinoshita recalled noticing that almost everyone around him looked relieved. So was he. He recalled thinking, "I won't have to die."

Todai closed after the surrender, and Kinoshita returned to his parents' home in Yonago. Over the next few months, the undergraduate read whatever books he could on quantum mechanics, including Paul Dirac's textbook *The Principles of Quantum Mechanics* and Hermann Weyl's *The Theory of Groups and Quantum Mechanics*. But food was scarce. "Many people exchanged expensive clothes for potatoes at nearby farmhouses," Kinoshita recalled, "but this didn't last long." Wild pumpkins were one of the few things that grew in the rocky soil, and after surviving on them for months Kinoshita acquired a lifelong distaste. But he was not unhappy when American occupation troops seized the Kinoshita family's land and redistributed it to the laborers, causing the family to fall from privilege to poverty, for it saved him from his familial obligation. Otherwise, as he told an interviewer decades later with a laugh, "I might have become the landowner of some small rice patch."

When Todai reopened in January 1946, conditions had scarcely improved, and many students and faculty had to live in offices and labs. Kinoshita was lucky, finding a room in the house of a cousin of his father. He was also thrilled to meet a physics friend with similar interests, Yoichiro Nambu, who had graduated from Todai in 1942, spent the war in a lab, and was still in uniform when he walked into the Todai physics department that spring. As there were no more formal courses for Kinoshita to take, he was able to spend all his time on research projects of his own devising. He was interested in the new quantum field theory, but Todai had no professor able to teach it. Kinoshita and a few other students with like interests managed to persuade Kunihiko Kodaira, a mathematical physicist with an academic knowledge of physics, to supervise them in the subject, and they scoured available journals for papers about quantum electrodynamics (QED). They discovered some that, during the war, had been imported into Japan from Germany by submarine, labeled "Top Secret."

QED had started to form around 1929 thanks to the efforts of Werner Heisenberg, Wolfgang Pauli, Dirac and others and was the basic theory of particle physics. At the time Kinoshita entered the field as an undergraduate, however, QED suffered from what Kinoshita called a "curious disease;" calculations using it produced infinities, also called divergences. Kodaira guided the students through all the cures for this disease that had been attempted. His seminars were long and demanding, starting after lunch and running late into the evenings. The only break was around 3 p.m., when Kodaira would make them all a pot of expensive black tea—rather than the more easily available green tea—and dropping in a moldy lemon, which was the only flavoring he was able to obtain. "I still remember the taste," Kinoshita recalled decades later, screwing up his face. He came to master QED so well that by the time he graduated in 1947 he was asked to talk to a physics seminar, his first such presentation.

Meanwhile, other gifted theorists were tackling the divergences. One was Sin-Itiro Tomonaga, a professor at the Tokyo University of Education, a forerunner of the University of Tsukuba, who was holding seminars on QED in the burned-out ruins of an army facility in the north of Tokyo after his own university had been destroyed. Kinoshita joined these seminars. Tomonaga's method for eliminating the divergences would earn him the Nobel Prize in Physics in 1965—for "fundamental work in quantum electrodynamics"—sharing it with U.S. physicists Richard Feynman and Julian Schwinger. Each of the three methods involved a method called "renormalization" of QED, which eliminated ultraviolet divergences by redefining parameters such as mass and charge to balance out diverging quantities. "I had the good fortune to watch at close range the exciting development of the renormalization theory of QED," Kinoshita wrote later.[1] Kinoshita began working on mass singularities, a kind of infrared divergence that appeared when the mass of a particle, hypothetically, is set to zero.[2]

In Japan at the time, only one alternative to Tomonaga's method had been proposed, known as the C-meson theory. Which was the right one? Curious, Kinoshita asked Tomonaga if experimental results might be able to decide between them, and Tomonaga took the time-honored educational strategy of assigning the person who had posed the question to figure it out. Kinoshita then discovered that the two methods were essentially indistinguishable up to a point but that the C-meson theory failed thereafter. Thanks to this work, the C-meson theory disappeared.[3] Kinoshita and Nambu then turned to calculating elementary particle processes based on the more and more robust versions of QED that were then appearing.[4]

Meanwhile Kinoshita supported himself by teaching physics at various places, including the Woman's Normal High School, which was the highest level of schooling women could attend. There he met and in 1951 married Masako "Masa" Matsuoka, a former physics student of his whose wealthy parents belonged to Japan's small Marxist community and who had been jailed during the war.

Institute for Advanced Study, Columbia, Cornell

Kinoshita received his Ph.D. from the University of Tokyo in 1952. On Tomonaga's recommendation, he and Nambu received postdoc positions at the Institute for Advanced Study (IAS) in Princeton, New Jersey. With little money for fancy passage, they took separate cargo boats to California and then crossed the country by train and bus. Masa stayed behind for a year to finish school.

At the IAS, Kinoshita and Nambu shared the same office on the second floor of the physics building. At the opposite end of the hall were Tsung-Dao "T. D." Lee and Chen-Ning "Frank" Yang, two Chinese physicists who had also arrived at the institute right after the war and who also shared an office. Lee and Yang were beginning to study a puzzle involving two particles that appeared to have the same mass and lifetime—which ordinarily would make them the same particle—but decayed via the weak interaction to final states with opposite values of a quantum number called "parity." This implied that the two particles had opposite values of parity, which contradicted the hypothesis that they were the same particle. Lee and Yang characteristically worked on problems by shouting at each other, which they did so loudly that Kinoshita and Nambu could hear them all the way on the other side of the building. Ultimately, Lee and Yang proposed that parity wasn't conserved in weak decays; this was soon verified experimentally in a famous experiment by Chien-Shiung Wu and resulted in Lee and Yang being awarded the 1957 Nobel Prize in Physics (that Wu, a woman, did not share it or get it on her own is now considered a historic injustice). Kinoshita began working on a calculational problem involving the discrepancy between the theory and experiment on the ionization energy of the helium atom.[5] The discrepancy was so large that it had led Enrico Fermi to postulate as an explanation the existence of a new force between electrons and the nucleus.

Masa was able to join Kinoshita at the end of his first year at the IAS, and they soon welcomed their first child, Kay, in 1954. Nambu then got a job at the University of Chicago, and Kinoshita took a postdoctoral position at Columbia University in New York City. His New York landlady could not pronounce Toichiro and began calling him "Tom," by which he became known in the United States.

At Columbia, Kinoshita continued his work on the He atom in an investigation that required one of the biggest numerical calculations at that time. To do so, he probably became the first theoretical particle physicist to write computer programs with FORTRAN, which was released in 1957, and he carried out his computations on the UNIVAC at New York University. Kinoshita's careful and extensive work uncovered a subtle error in the previous analysis of the He atom.

In 1956, Kinoshita was offered a job at Cornell University in Ithaca, New York, where he would spend the rest of his career. There, he and Masa had two more daughters, June in 1958 and Ray in 1960. Dismayed by the fact that no Asian foods were available in Ithaca, Masa helped operate a food coop to bring in tofu, Kikkoman soy sauce, and other staples. Kinoshita continued to be principally dedicated to his work. "We knew that his first love was physics, second his wife and maybe a third, his daughters," Ray once said, "and we were OK with that." He was a devoted father but also strict, worried that his daughters would become typical rowdy American teenagers.

Kinoshita, meanwhile, had mastered Feynman's calculational method, which had grown into the standard and which graphically represented in diagram form the different amplitudes that needed to be calculated and summed together to determine the behavior of subatomic particles. The diagrams were a convenient way to keep track of the incoming states, the outgoing states, the virtual intermediate states that are emitted and reabsorbed, and all the integrals that need to be performed. At Cornell, Kinoshita developed a systematic way of evaluating the integrals, summing the amplitudes, and handling all the infinite divergences such that the final result of the calculation was finite. In one of his papers, he proposed a new method for handling mass singularities; this represented a significant theoretical breakthrough, and the paper has over 1,000 citations to date.[6] This idea was further developed by T. D. Lee and Michael Nauenberg and is now a fundamental theorem of QED known as the Kinoshita–Lee–Nauenberg theorem. The puzzle of mass singularities, and how to eliminate them, would remain on Kinoshita's mind and figure into the rest of his work. Kinoshita also tapped his earlier work on mass singularities to renormalize calculations of the decays of various particles, such as muons and pions.[7,8] Feynman himself visited Cornell in the fall of 1958, and during his visit there Kinoshita became one of the rare individuals to uncover an error in Feynman's calculation.[9]

In 1962–63, Kinoshita took his family to CERN, the international physics laboratory outside Geneva, Switzerland, on a Ford Foundation fellowship. There he would work five days a week and Saturday morning, as per his habit, then take his family on trips to the French or Swiss countryside. He was an avid downhill skier and transferred the skill to his daughters.

G-2

In 1966, Kinoshita returned to CERN as a visiting scientist, again bringing Masa and his three daughters. The direction of Kinoshita's research now took a sharp turn. On one of his first days at the lab he became set on the path that would absorb him for the next six decades, and eventually make him famous among physicists. Theorist John Bell had arranged for the new crop of visiting fellows to tour CERN's experimental facilities. The group's first stop was at the synchrocyclotron, where a team of physicists had recently issued the final report of their measurement of *g*-2, a number based on how muons slowly change their rotational axis in a magnetic field, which is known technically as "precession" and popularly as "wobble." Its measurement was made possible by parity violation in the weak interaction, the discovery of which was an outcome of Lee's and Yang's loud conversations at the IAS. Parity violation was a bountiful gift to experimenters, who could put it to work in a variety of ways, such as using it to measure *g*-2.

Calculating and measuring *g*-2 was vitally important to QED. By this time, it had grown into a theory central not only to physics but, by extension, throughout the sciences. As Kinoshita wrote later in *Quantum Electrodynamics*, it provided the foundation for "the quantum mechanics of atoms and molecules as well as condensed matter physics, not to mention their numerous applications in chemistry, biology, etc.," and was becoming *the* theory of high-energy physics as well as the prototype for any quantum field theory. When describing the behavior of a particle such as an electron or muon, QED incorporates the effects of invisible or "virtual" particles interacting with it. By far the most precise way for experimenters to test this idea is to measure the way that muons behave in a magnetic field. In it, the direction of the muon's spin (or internal angular momentum) is no longer constant and rotates with respect to the direction of the linear momentum. This rotation, called precession, can be measured thanks to a consequence of parity violation, and the value of the precession is proportional to the ratio of the muon's magnetic moment to its spin, which is known as "*g*." A precession would not show up if *g* were equal to 2, and its presence implies that *g* differs from 2. This difference, which results from the effect of virtual particles, can be calculated in QED. But if Nature contained new physics—particles or forces not in the theory—it could show up as a difference between the muon's measured precession and the QED prediction. The striking thing about *g*-2, as Kinoshita wrote in *Quantum Electrodynamics*, was "the fact that it is one of the few quantities that can be measured very precisely and, at the same time, is calculable from first principles." From precession, precision.

The CERN experimenters used a variety of tricks to improve the precision of measuring muon wobble/precession. They had begun their muon *g*-2 experiment in 1959, obtained their first results in 1961, and had progressively refined their measurement, issuing a final report in 1965. It was such an important measurement that it drew the attention not only of periodicals such as *Scientific American* but also of popular media such as the Swiss newspaper the *Neue Zürcher Zeitung*. But the measured value was extremely close to the theoretically calculated value, too close, and did not indicate what physicists had hoped: that QED would break down, and that the muon felt an additional force, which would explain its difference from the electron. But it was possible that a more precise calculation of the theoretical value of *g*-2 would turn up a discrepancy between the experimental and theoretical values, and thus something scientifically interesting.

The existing calculations had taken into account only the effects of muons, electrons, and photons. These are the largest contributors to the precession, and they comprise what is known as the fourth-order calculation, which involve cases in which the muon or electron emits or absorbs a photon a total of four times. Photons that are emitted by a muon are represented as looping around to be reabsorbed by the same muon. This makes the order of a calculation always an even number. A more precise calculation would need to complete a sixth-order calculation, which would require figuring out the types of Feynman diagrams involved and summing them. The CERN experimenters had crafted together a variety of highly ingenious tricks to measure *g*-2 by the way it precessed/wobbled. Now they wondered if an equally ingenious physicist might be able to assemble enough computational tricks to calculate the theoretical value. Not sure whether it could even be done, they tacked their results to the wall of their lab. [Figure 2]

Enter Kinoshita. When the group of new visiting scientists stopped at the synchrocyclotron, he stared at the graph of the results. It stunned him, for he realized that his work on mass singularities, which he had done while in Tomonaga's group and finished at Cornell, along with his knowledge of renormalization, Feynman diagrams, and computer programming, gave him most of the tools necessary to calculate *g*-2. He realized that the two lowest orders, the second and fourth, were already known and could be found in published results. To get to the sixth order, one would start by multiplying them and incorporating an enhancement factor coming from what was known as vacuum polarization, the virtual creation and annihilation of electron-positron pairs. Kinoshita promptly dropped out of the tour at its first stop! Invited to a prestigious relatively new international laboratory, and summoned to a tour by the lab administration, Kinoshita had dropped out at the first opportunity and headed for the library. He returned the next morning and announced to the experimenters that he knew how to calculate what they wanted.[10]

Incorporating the second and fourth orders was only one piece of the calculation. The second piece involved a new type of Feynman diagram that appeared in the sixth order for the first time, called a light-by-light vertex diagram. Incorporating it involved the most complicated and lengthy calculations in the sixth order, which required him to tap the knowledge he had acquired in his work on He of how to carry out numerical calculations using a computer, as well as his knowledge he had developed in using complicated Feynman diagrams to eliminate mass singularities. He and collaborators published the results of these two pieces in 1969, correcting their earlier work.[11] This paper marks the first results of Kinoshita's foray into *g*-2 calculations.

But the full calculation of the sixth-order g-2 required a third piece. This involved removing divergences that entered via another route. According to the Kinoshita-Lee-Nauenberg theorem this, too, had to be solvable, and Kinoshita succeeded by summing fifty Feynman diagrams of a new kind; he also had to show that the calculation preserved gauge symmetry, which is the bedrock of QED. With a graduate student, Kinoshita was then able to establish a calculation method that worked to any order of QED and was essentially the same for electrons and muons. It was announced in 1972 and was the first calculation of the entire sixth-order diagrams.[12] They kept improving their sixth-order QED calculations, establishing how to calculate *g*-2 numerically with computers.[13,14,15]

Meanwhile, when Masa found that her children were finally old enough to manage being at home unsupervised

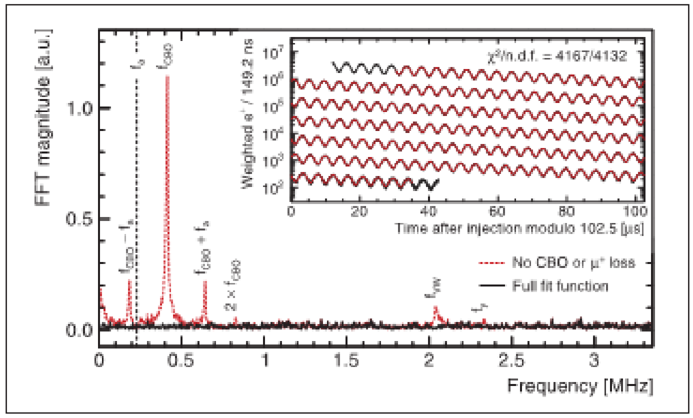

Figure 2 Graph of the muon's precession, from Abi, B., et al. 2021. Measurement of the positive muon anomalous magnetic moment to 0.46 ppm. (Muon *g*-2 collaboration). *Phys. Rev. Lett.* 126, 141801. In 1966, Kinoshita saw a much earlier version of this graph.

for the afternoon, she bought a loom and started handweaving. Within a year or so, she was good enough to win grand jury prizes but was uninterested in becoming commercial. In 1973–74, when Kinoshita spent a year as a visiting professor at the University of Tokyo, Masa took up kumihimo ("gathered threads"), a traditional and until then nearly forgotten Japanese textile artform. This technique involves making braided cords using a special stand and weights and had been known for centuries in Japan. But the technique of creating the cords by hand was forgotten. In Ithaca, Masa worked at the library of Cornell University and was in charge of dealing with Asia-related books. She found a reprint of the book *Shika-suu-you*, edited by a feudal lord in the nineteenth century, and in it discovered the forgotten kumihimo hand-technique and successfully replicated it in practice. She named this hand-manipulation technique *kuteuchi*, or "hand loop," and developed it using her mathematical background.

Kinoshita's working-week habit continued—Monday to Saturday mornings—but occasionally now he and the family would follow Masa when she went to do research on kumihimo at museums or workshops or exhibitions. Kinoshita would continue to refine the sixth-order calculations for the next twenty years, until his retirement. A final report appeared in 1995.[16]

During this time, CERN scientists mounted two more experiments to measure *g*-2, and then, starting in 1984, one at Brookhaven National Laboratory in the New York. (A subsequent measurement, at the Fermi National Accelerator Laboratory, would never have been attempted had there been any doubt about Kinoshita's calculations.) These experiments were extraordinary. A series of freaky coincidences had made it possible to measure the number to spectacular precision, and Kinoshita's diligence and synoptic grasp of the fundamentals of QED made him able to calculate it to spectacular precision. The comparison of the two made for extraordinary science.

Meanwhile, Kinoshita turned his attention to a related issue, the *g*-2 of the electron; his work was as valid for the electron as the muon. Experimenters at the University of Washington sought to measure the electron's *g*-2 hundreds or even a thousand times better than previous measurements —which was much more difficult measure. But because the electron *g*-2 does not involve contributions from quantum chromodynamics (QCD), Kinoshita's calculations are the end of the story for that. A theorist would have to calculate eighth-order QED, which would involve the 891 Feynman diagrams. Kinoshita was the only one who had calculated the sixth-order QED term for both the electron and muon. Could he do the eighth-order term for the electron? The task was enormous, but he was determined to try and enlisted the help of graduate students. Most of the 891 Feynman diagrams could be handled with the calculational method he had developed for the sixth-order term, but some new diagrams with divergences appeared that also had to be mastered. Hans G. Dehmelt and his team at the University of Washington successfully measured *g*-2s of a single electron and a single positron in 1987; the Nobel Prize was awarded to Dehmelt two years later.

Kinoshita published the first numerical result of the eighth-order term (-0.8 ± 2.5) in 1981,[17] and he continued to refine the calculation in six publications over the next decade. For his work, and over the next four decades, he developed new programs and used supercomputers at Cornell University, Brookhaven National Laboratory, the High Energy Accelerator Research Organization (KEK), RIKEN, and many others.

By this time, Kinoshita had returned from the theoretical study of electron *g*-2 to the study of muon *g*-2, tackling the eighth order.[18] His work on the sixth order had been so systematic that it laid out the basics for the eighth-order calculation. But it involved yet more new kinds of difficult Feynman diagrams, in particular ones involving the contributions of hadrons, and he would work on it, with collaborators, for the next two decades.[19,20]

No Retirement

One of us (Nio) entered Cornell University in 1990 and began studying with Kinoshita as his last student. Kinoshita's habits, as always, were methodical. Monday through Friday, he came into his office at 9:00 a.m. and left at 5:00 p.m. to pick up Masa, and the two drove home together. Unless he was teaching or attending seminars or talks, he was always in his office working on physics, reading journal articles, doing calculations, or writing research papers. A graduate student could visit him anytime without appointment.

Kinoshita always spoke in a slow, calm, and quiet tone. He went out of his way to make young female students comfortable with discussing physics with an elder male and famous professor. A graduate student would start by writing equations on his small blackboard. Kinoshita was not an easy person to convince, and often highly critical. Sometimes he would agree with the student's work, while at other times he exposed flaws in the conclusions and requested that the student return the next day with new ones. But students loved the process, as did he.

Kinoshita was always skeptical of any new results no matter who the authors were—not until he analyzed the results himself. Cornell physicist Peter Lepage recalls that, when Kinoshita discovered a discrepancy between another group's work and his own, he would redo his entire calculation from scratch to make sure that he hadn't made a mistake. If he hadn't, he would redo the other calculation the way they had done it to see if they were the ones who had made a mistake. This could take months and was something few others would have done. One way or another, Kinoshita hunted down the error. He did the same with the work of students. He and the students would do even the smallest calculations independently, and only when they were in perfect agreement would he let the students proceed. Another piece of advice he would give them is that they should always proofread a paper at least a hundred times before submitting it to a journal. They found that advice difficult to follow.

Kinoshita retired from Cornell in 1995 and became a professor emeritus. Afterwards, he and Masa took a trip to China to attend a conference and then toured the Silk Road. He had developed an avid interest in Chinese and Japanese archeology and overcame his usual aversion to travel to brave a long trip by rail and overland to get to the Mogao Caves, known for their millennia of Buddhist art. He later told people that during that trip, for the first time in his life, he did not think about physics at all. It didn't last. Upon returning to Cornell, he announced that he would do nothing but physics research, despite his retirement. By this time, evidently, he had decided that he would tackle *g*-2 to the tenth order.

In 2002, Kinoshita and Nio began to develop more sophisticated computer programs to evaluate some of the most difficult eighth-order *g*-2 diagrams so as to provide a general solution. The software could not just calculate the diagrams but come up with them. Using the new software, they were finally able to calculate something in the eighth order that they could only estimate before. The software also made it easier to extend QED calculations to any order and was an important step toward the tenth-order QED calculation, which they soon began to tackle. Kinoshita and Nio started working on the tenth-order QED *g*-2 by classifying 12,672 diagrams into thirty-two subsets, and the two soon obtained the dominant

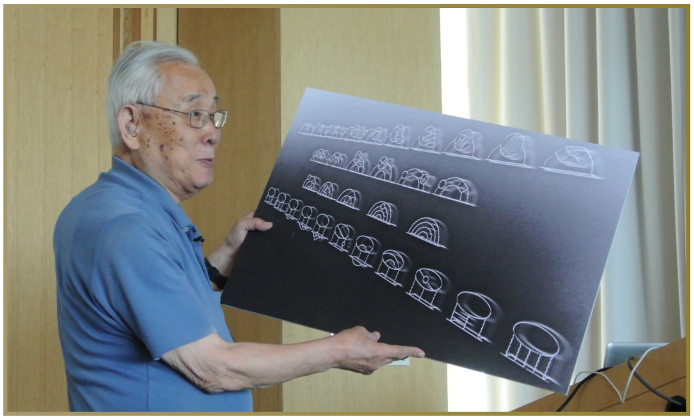

Figure 3 Kinoshita holding photo of a sculpture of his Feynman diagrams, by Edward Tufte.

contribution to the tenth-order QED of the muon *g*-2.[21] Kinoshita and collaborators published nine more papers on the tenth-order from 2008 to 2012.[22,23] The year Kinoshita died, one of many sculptures of diagrams from these papers made by the statistician and artist Edward Tufte was installed in the Physics Department at Cornell University. [Figure 3]

Kinoshita learned or invented whatever tools he required, whether they be analytical techniques or computer programs. As his *g*-2 results got more and more precise, he needed more and more calculations of other areas of QED and taught himself how to carry them out, becoming one of the biggest supercomputer users in the world. He was thrilled with the popularity of string theory among theoretical physicists, for even though he was growing older in a field built for the young it meant he had no competition in sight on his quest to calculate one of the most important questions in physics. Kinoshita became ever more high-profile as the go-to person for understanding the foundations of QED and as *g*-2 itself became an ever more high-profile number, as experimenters were eking out fewer surprises. In 2018, at the age of ninety-three, he published a paper in *Physical Review* refining his calculation of *g*-2 to the tenth order,[24] and the year after, he published his final paper, in *Atoms*, on the general theory of *g*-2 calculations to all orders.[25]

Over half a century later, the theory and measurement of muon *g*-2 remain one of the most important tasks in physics. As many new models for fundamental particles imply a change in the value of *g*-2, the measurement erects "a constraint on the fantasy of theorists," as one of its experimenters wrote. According to Kinoshita, the theory of quantum electrodynamics has exhibited "remarkable resilience" when tested against the flint of "rigorous experimental tests." Still, he added, "It is important to keep pushing the limits; new physics might reveal itself in [*g*-2's] next decimal place in theory and measurement."

Kinoshita was periodically nominated for a Nobel Prize. He never received it. One reason is doubtless that his contributions to physics, though indispensable, are difficult to label, and another is that his contributions did not change our understanding of QED even while driving it forward. Physicists hugely benefit from those who are intimately familiar with the resources, methods, and techniques, and how these intertwine, in the foundations of their field. Such people are frequently sought out as a resource and propel the discipline forward but are not as readily categorizable as discoverers or theory-creators. Kinoshita was like a thoroughly reliable, trustworthy, and essential architect-engineer who tends to the foundations of a community building, most of whose occupants work more visibly on higher floors.

Kinoshita's daughter Ray, an architect, built a house in Amherst, Massachusetts, with an attached apartment for her parents, but it took her years to convince Kinoshita to stop working at Cornell and move in. He finally did, reluctantly, in 2014, at the age of ninety; the University of Massachusetts made him an adjunct professor and gave him an office where he continued to work almost every day. Until the end of his life, he had a meticulous gentleness to how he would brush his hair, wipe his mouth after a meal, and put on his hat to set out on a walk. He never stopped being conscientious about the world around him; when his granddaughter Emilia diligently wrote letters to her ojiichan (grandfather) as she was learning Japanese, he would immediately if tenderly point out the errors. But he was also alert to the follies of the world around him, and a softening of his face and liveliness of the wrinkles around his mouth signaled that a laugh was imminent.

The world is infinitely complex, he would say. Any theory devised by humans, such as QED, had to break down somewhere, and calculating *g*-2 to unprecedented precision was his way to provoke experimenters to find it and theorists to improve it. At the time of his death, Kinoshita knew there would be more orders to reach, more Feynman diagrams

Figure 4 The headstone at the urn site of Toichiro Kinoshita and Masako Matsuoka in Ithaca, New York.

to sum, and more decimal points for experimenters to seek and for theorists to measure themselves against and fret over. Also, calculating the next order—the twelfth—will require a better understanding of the contributions from QCD than we have now. Kinoshita took *g*-2 calculations as far as they can possibly go for a very long time.

Masa died in 2022, and Kinoshita in 2023. Their urn is buried in Ithaca, near Cornell. Its headstone was designed by Ray and by Ray's daughter Emilia, a designer and materials researcher. The urn is decorated with images from Tom and Masa's work: a sixth- and tenth-order diagram, one of whose lines leads into a Kumihimo diagram from Masa's book on Japanese braiding.[26] Their headstone also has these images, which embody some of the deepest shapes and rhythms of the unruly world that the two lived through and explored. [Figure 4]

Acknowledgments

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