Preface:
Nonlinear waves in honor of Harvey Segur on the occasion of his 80th birthday

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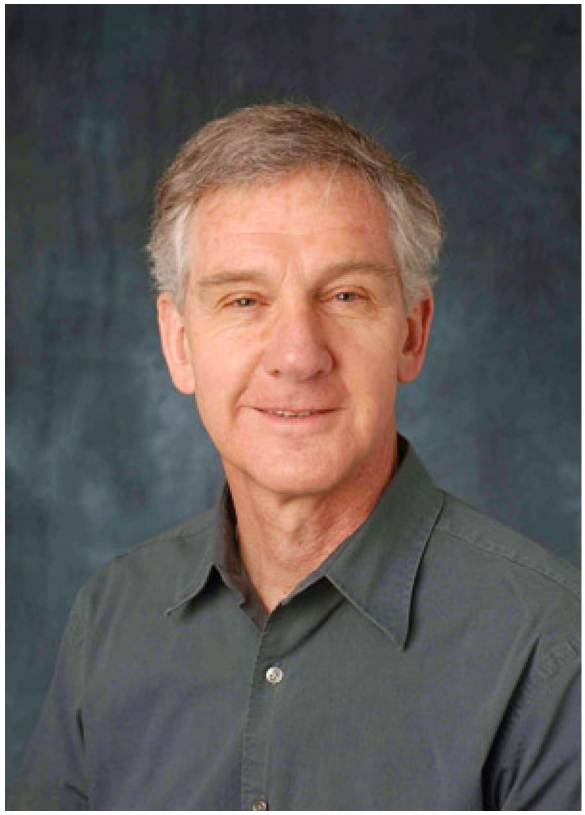
This special issue of *Studies in Applied Mathematics* is dedicated to Professor Harvey Segur on the occasion of his 80^{th} birthday. Harvey is a world-renowned applied mathematician who has had a great impact on the field of nonlinear waves as a researcher and on the next generation of applied mathematicians as an acclaimed teacher.

Everyone in the nonlinear waves and coherent structures community is familiar with the book Harvey co-authored with Mark Ablowitz entitled "Solitons and the Inverse Scattering Transform" [5]. When it appeared in 1981, Benno Fuchsteiner reviewed it for *Mathematical Reviews* and argued that it will remain the best introduction to the area of soliton equations for a long time. At this point, forty years later, the statement remains accurate: the book is a classic, and leads an ever-growing pack of potential successors. To date, according to Google Scholar, it has over 5,300 citations. Soliton Theory has often been called one of the two major breakthroughs in nonlinear science in the twentieth century, the other being Chaos Theory. It is beyond doubt that this book has been a major contributing factor in establishing Soliton Theory in this distinguished position. It has served as the introduction to the field for many in the discipline, while making many different aspects of it accessible to a large audience of scientists from such distinct disciplines as oceanography and electrical engineering.

As a researcher, Harvey has never followed popular trends. He studies problems that have sparked his interest because of their intriguing physics or mathematics. Often these problems are hard, to the extent that they are avoided by others. In many cases, they lead to areas of mathematics that are not considered "standard fare" for applied mathematicians. Harvey often has learnt new mathematics to deal with these problems. Equally often he has developed new mathematics to deal with them. As such his work has on several occasions resulted in the start of a new branch of applied mathematics. We will single out several such cases.

AKNS: Soliton Equations made methodical. In 1974, Mark Ablowitz, David Kaup, Alan Newell, and Harvey Segur (AKNS) published a seminal paper "Inverse Scattering Transform – Fourier Analysis for Nonlinear Problems" in *Studies in Applied Mathematics* [6]. In previous years, Martin Kruskal and coworkers [16] (see Chapter 1 of [15] for



Harvey Segur in 2017.

Harvey Segur teaching.

an introduction to this history) had established many extraordinary properties of the so-called Korteweg-deVries (KdV) equation, a nonlinear partial differential equation that can be used to model the dynamics of one-dimensional waves in shallow water. As we understand the history of the subject, their discoveries were initially regarded as flukes, confirming the KdV equation as a truly exceptional equation. In 1972, Zakharov and Shabat [29] demonstrated that the nonlinear Schrödinger (NLS) equation (which arises in even more applications than the KdV equation) was as special as the KdV equation. The AKNS paper demonstrated that both the KdV and the NLS equations were members of a large class of equations, all of which share, or have analogues of, the special properties found by Kruskal et al. for the KdV equation. This methodical approach was the main achievement of the AKNS paper. It also established that the solution method developed by Kruskal et al. was a generalization of the Fourier transform method which is so important in physics and engineering. This paper was one of the primary catalysts in establishing Soliton Theory as an area of applied mathematics, as opposed to a collection of curiosities. Worldwide, every major university houses a few soliton specialists, or some researchers who use results from and contribute to Soliton Theory. Since the applications of Soliton Theory are widespread (Biology, Chemistry, Engineering, Physics, etc.), these researchers are found in many different departments. Currently, Google Scholar lists more than 3,100 citations for the AKNS paper.

Painlevé Transcendents: Testing for integrability. Starting in 1977, Harvey published a series of several papers (some with Mark Ablowitz and Alfred Ramani, e.g., [4, 1, 2, 3, 9]) connecting the classical work of Painlevé and coworkers to the theory of solitons. To date, Google Scholar lists over 2,000 citations to these papers. After the development of Soliton Theory, one of the main remaining issues was the lack of an explanation: "What makes these equations special? Why do they have all these special properties? How could one determine whether a given equation is a Soliton Equation?" The best answer to this question remains that provided by these papers, which connects Soliton Equations to classes of equations studied by Painlevé et al. 80 years earlier for mathematical reasons. After the studies of Painlevé et al., these equations were mostly ignored, because they did not arise in applications. The work of Harvey Segur and collaborators brought this work back to the forefront. This resulted in a good understanding of what makes Soliton Equations special (the singularity structure of their solutions) and it provides an easy test to determine whether a given equation is a Soliton Equation. Painlevé analysis and the Painlevé equations are now a rich part of applied mathematics, connected with as many applications as Soliton Theory.

Asymptotics Beyond All Orders: In the mid eighties, Martin Kruskal and Harvey Segur [23] examined a problem arising in crystal growth. This problem contained a small parameter ϵ, so they were naturally led to consider solutions to the problem as a power series in ϵ. This approach failed, as the effects of the parameter ϵ could not be captured using any finite power of ϵ. Martin and Harvey introduced the concept of Asymptotics Beyond All Orders to tackle exponentially small phenomena like this. This involved several deep ideas about the singular behavior of solutions of such problems in the complex plane. The method initiated in their paper on this topic has added a powerful tool to the classical areas of Perturbation Theory and Asymptotics. It has significantly enlarged the class of problems that can be approached with Perturbation Theory, see [26]. Current publications in this area are still dominated by Asymptotics Beyond All Orders. The number of citations to these two key papers is lower than those mentioned above: not only are these contributions more recent, they circulated in the applied mathematics community in the form of a preprint for a long time to which many researchers refer instead. The influence of Asymptotics Beyond All Orders will be very significant in the long run, as its applications are not restricted to any specific class of equations.

Another hallmark of Harvey's work is his interest in applying his work to physical systems and getting it right. He uses experiments both to test and guide theoretical work, and when predictions from theory disagree with measurements, he does not let up until he understands on a fundamental level why they do not agree and how the theory can be improved or fundamentally changed. Of special note are his classic works in the 70s with Joe Hammack [19, 20] on comparisons of KdV predictions to long one-dimensional waves, and in the 80s/90s with Hammack and Scheffner [18, 17] on comparisons of KP predictions to long, weakly two-dimensional waves. Results from this work continue to intrigue Harvey; he is working with tsunami modelers [7] to understand the role of dispersion in forecasting tsunamis. His recent work [25] with Hammack, us, and others on comparing one- and two-dimensional NLS predictions to experiments on deep-water waves and published observations of dissipation of ocean swell has led him to re-think the role of the classical Benjamin-Feir instability and more broadly, the role of dissipation in modeling ocean swell.

In addition to the scholarly contributions described above, Harvey has made important contributions to applied mathematics through teaching, advising students, and leading workshops. He regularly teaches courses in Asymptotics and Soliton Theory at the University of Colorado at Boulder where he is a Presidential Teaching Scholar (the highest teaching award in the CU system). In 2011 he received the Hazel Barnes Prize, the highest faculty recognition for teaching and research awarded by the University of Colorado. In 2006, Harvey led a workshop on Nonlinear Stability as part of the SIAM Workshop on Stability and Instability of Nonlinear Waves; in 2008 he was Principal Lecturer for the NSF/CBMS Conference on Water Waves: Theory and Experiment; and in 2009, he was co-Principal Lecturer with Roger Grimshaw at Woods Hole's summer GFD program on Nonlinear Waves. Through leading lecture series like these, he passes his knowledge and approach on to the next generation of nonlinear waves researchers. At research conferences, Harvey is continuously approached by others who solicit his opinion. In many cases he has never met these researchers. He is always patient and willing to listen, often providing the valuable input that was hoped for. Harvey Segur was the PhD advisor of three students (two of which co-edited this special issue and co-authored this introduction). Harvey's mentoring exemplifies the passing on of scientific knowledge, curiosity, doggedness and ethics. He does not believe in role models, but he is one of the best one we know of for future generations of applied mathematicians.

This special issue is composed of eleven papers written by some of Harvey's mentees, collaborators, and others influenced by his work. The papers cover a subset of the many research areas and methodologies Harvey worked in, including theoretical models of water waves, comparisons between model predictions and experiments, the inverse scattering transform and related methods, and integrable partial differential and difference equations.

It is a wide ranging collection of contributions, reflecting Harvey's approach and wide range of interests.

The first paper by Boulton et al. [8] examines the so-called Talbot effect or dispersive quantization in the context of three linear but nonlocal partial differential equations, all of which are used in different regimes of water wave theory. The next contribution by Cisneros & Deconinck [10] examines the discrete Unified Transform Method (developed by Fokas, another contributor to this special issue, in 1997 [12]) as a starting point for finite-difference numerical methods for boundary value problems for nonlinear partial differential equations, allowing one to account for the given boundary conditions. The third paper, by Crisan, Holm & Street [11] derive new equations modeling free-surface motion that are not restricted to potential flow, allowing for wave-current interaction. All of this is done within a Hamiltonian framework, as is often preferred by Harvey. The paper by Fokas & van der Weele [13] revisits linear evolution partial differential equations with time-periodic boundary conditions, reminiscent of a wave tank. Remarkably, the Q-equation approach used by the authors allows for the derivation of the results of other authors in an purely algebraic way. Next, Ford et al. [14] develop and examine a molecular dynamics model of airway mucus, allowing for the exploration of the clinical evidence that points to hyperconcentration instead of pH as the primary cause of structural changes within the mucus. The sixth paper by Henderson, Catalano & Carter [21] examines laboratory generated, bi-periodic patterns of waves that propagate in the x direction with amplitude variation in the y direction using the uniform-amplitude solutions of the vector nonlinear Schrödinger equation and the Jacobi elliptic sine function solution of the scalar nonlinear Schrödinger equation. They show that the comparison with the elliptic function solution of the sNLSE has significantly less error. Next, Joshi & Nakazono [22] start from Hirota's inconsistent but integrable discrete KdV equation. Introducing new transformations, they find related integrable discrete equations that, remarkably, are consistent. The paper by Lester et al. [24] studies periodic generalizations (chains) of the famous lump solutions of the Kadomtsev-Petviashvili (KP)-1 equation, one of Harvey's favorite playgrounds. Using a Grammian form of the τ-function they investigate the dynamics and interaction of such lump chains, showing that the KP equations have not revealed all their secrets yet. The contribution by Trogdon [27] revisits the famous AKNS paper [6] and makes the forward and inverse scattering transforms introduced there computationally effective using rational functions. The penultimate paper by Vasan, Manisha & Auroux [28] follows up on a conversation with Harvey to revisit the inverse water wave problem of reconstructing the bathymetry from surface measurements. Finally, the paper by Zaug & Carter [30] is an extension of Harvey's thought-provoking work demonstrating that adding any amount of (the right kind of) dissipation stabilizes the Benjamin-Feir instability [25]. By comparing with a classical set of ocean swell data, Zaug & Carter showed that dissipation is needed to accurately model the evolution of nearly-monochromatic wave trains as they travel long distances.

During the summer months of 2020, we led a series of conversations with Harvey Segur over email, phone, and Zoom. The conversations were edited for length and clarity. Our questions are in boldface, followed by Harvey's answers in regular font. The opinions expressed herein do not necessarily represent the opinions of the interviewers, editors, or journal.

- **Tell us about your childhood.** I grew up in Oak Park. It is a fairly wealthy suburb of Chicago that had a high opinion of itself.
- **When did you discover your interest in engineering and mathematics?** My father ran a small business, focused on industrial engineering. A major in engineering was highly recommended in our house.
- **Did you have any K-12 teachers that inspired you?** Yes: Mrs. Forster (first grade, very kind & generous); and Lola L. Lindsey (Calculus, she forced me to work up to my ability, and I am grateful for her high standards).
- **Tell us about your time at Michigan State (MSU).** Growing up in the Midwest, I wanted to go to a Big 10 University, but not U. of Illinois, where half of my high school class went, and not Michigan, where my older brother went. I had a good time at MSU, and I learned about myself and about real life there.
- **Tell us about your time in Southern California and being a graduate student at Berkeley.** I graduated from MSU with a Bachelor's degree in Mechanical Engineering. Here again, I wanted to avoid the same old stuff. The space program was new and exciting in the 1960s, and San Diego was very different from the Midwest. I spent one year working in San Diego, and I learned a lot about aeronautical science, about Southern California, and especially about what I did or didn't want to do with the rest of my life. My time there was very enlightening. It was the first time I had taken a job in industry, not related to my father's company.

  Berkeley was wonderful! There was a LOT going on Berkeley in the 1960s, and the academic standards there were much more serious than anything I had experienced before. I also met Carol [whom he married a few years later] there. We left there immediately after getting married. Both of us appreciated the experiences we had while living in Berkeley. Those were interesting times.
- **Why did you decide to study aeronautical science at Berkeley?** Mechanical Engineering at Berkeley had 4 "divisions"; Aeronautical Sciences was the division that focused on fluid mechanics. Given what I had learned in San Diego, I wanted to learn more about the variety of problems in fluid mechanics.

  When I was a graduate student in Berkeley, there was a big meeting, held at Stanford, on fluid mechanics as I recall. One of the speakers at this several-day meeting was a young man named Robert Miura. He talked about some work he had been doing as a post-doc at the Plasma Physics Lab (PPL) in Princeton. He was working on an equation called the Korteweg-de Vries (KdV) equation. As I recall, he explained one of the many things he did while he was at PPL but I no longer remember which big break-through he had presented at this meeting. I did not follow everything he said, but it was intriguing, and different from anything I had seen before.

  About the same time, I was taking a course taught by John Wehausen on water waves, and he brought up an equation that is relevant to water waves, called the

Korteweg-de Vries equation. I was amazed and pleased to learn that this equation has unusual mathematical properties and is also important as a model of a physical process in shallow water. I didn't know that such things happen, but here they are.

- **Tell us about your time at Caltech.** Gil Corcos, my thesis advisor in Berkeley, was an old friend of Gerry Whitham, who was the Chairman of Applied Math when I was there. Moving to Caltech allowed me to switch from Mechanical Engineering to Applied Math, in a very well-known department, working with one of the leading figures in Applied Math. Fantastic! Even so Caltech, like Oak Park, had a high opinion of itself, with some justification.

  When I met the famous Whitham, he had just returned from a meeting at the Plasma Physics Lab in Princeton. At this meeting, he heard a talk by someone named Martin Kruskal, who presented work by himself and another person named Norman Zabusky. My impression was that Whitham had heard Kruskal present their work, he had recognized that Kruskal was doing something he had never seen before, but he had not yet figured out what it was that Zabusky and Kruskal had actually done.

  This was not so long after I had arrived at Caltech, so Whitham and I had not discussed what I should do while I was at Caltech. Then one day he told me to stop doing what I had been doing, and to read a paper by Zabusky & Kruskal instead. That was enlightening, and it got me further into integrable problems.

  In addition to meeting Gerry Whitham, Phillip Saffman, and other famous mathematicians at Caltech, I also met a graduate student in Civil Engineering, who happened to live in the same apartment building in which Carol and I were living. His name was Joe Hammack, and he was working on an experimental thesis, to model the behavior of tsunami propagating over long distances in the ocean. His thesis advisor was Fred Raichlen. What a great coincidence: I was working on learning the mathematical mysteries of the KdV equation, which describes long waves that propagate in shallow water, and Joe was carrying out experiments on long waves propagating in shallow water.

  It's always been true that I am curious about the hidden wonders in the world of mathematics, but I get more excited when wonderful mathematics happens to line up with physical applications. At some point, Joe went over to meet Gerry Whitham, to explain to him what he saw in his experiments. My impression was that Whitham's opinion of me went up somewhat after he had met with Joe (and maybe also Raichlen).

- **Water waves seem to be the application that you always come back to. Why are you drawn to them?** As mentioned above, I enjoy learning about the logical structure that is waiting to be found in mathematical analysis, but if you stop there, then mathematics can degenerate into clever puzzles. I'm much more impressed when the mathematics relates to physical processes, and especially to physical processes that one can see in everyday life. For example, the KdV equation describes parts of plasma physics and parts of water waves, but one can observe the physical processes of plasma physics only if one has the massive set of equipment needed to "see" anything about plasma physics. That is a large part of my interest in water waves – everyone knows what a water wave is.

- **How did you end up at Clarkson?** How I got to Clarkson is an interesting story. Alan Newell had completed his PhD at MIT, working under Dave Benney. Then he went to UCLA as a hotshot Assistant Professor in the Math Department there. My impression is that the Math Department at UCLA was not the right place for Alan Newell, or vice versa. The Applied Math faculty at Caltech had a lot of interaction with mathematicians at UCLA. Alan was looking for a suitable position after UCLA, and someone at UCLA pointed out to Alan that the Math Department at Clarkson College, WAY upstate in New York, was looking for a new Chairman. Clarkson was known for its hockey team, and its Chemistry Department was good (but not as good as the hockey team). Alan's thesis advisor, Dave Benney, was a good friend of Gerry Whitham. My impression was that Gerry Whitham was not all that fond of me, and here was a chance for him to unload this postdoc on a small school that no one knew anything about, almost as far away from southern California as we could get without leaving the contiguous United States. When Alan moved to Potsdam, NY, he brought with him two other applied mathematicians, Mark Ablowitz (another student of Dave Benney) and me. Mark and I began our teaching careers on the same day, at Clarkson College.

  Already when we were in the process of moving there, Alan Newell was in the process of working out an extended meeting in Potsdam on what are now called integrable PDEs. I didn't know that he had that plan in mind until I got there, and he didn't know that I had been working on the KdV equation. What a fortunate coincidence. The Potsdam meeting was great. The main speakers at the conference included: Brooke Benjamin, Dave Benney, Martin Kruskal, Peter Lax, and Gerry Whitham. What a great way to find out about a new subject, called integrable problems. In addition to a stellar list of main speakers were several less famous people who were already working on various kinds of integrable problems, including Mark Ablowitz, Cliff Gardner, John Greene, Rich Haberman, Dave McLaughlin, Robert Miura, Norman Zabusky and others. At this point, integrable problems were on their way.

- **What happened after Clarkson?** After 5 years in the Math Department at Clarkson, Carol and I had had enough of the craziness at Clarkson. I learned that a small company in Princeton, NJ was looking for someone who knew about fluid mechanics and about constructing mathematical models of fluid mechanical situations. I joined that company and worked there for about 8 years. This was the second time I had worked in an industrial setting. At the same time, I made connections with Martin Kruskal and John Greene, both of whom worked at the Princeton Plasma Physics Lab, so I split my time between the work of the company (supported by contracts with government agencies like the Environmental Protection Agency), and the work related to integrable problems (supported by my grant from the NSF). In some ways, this was an ideal situation. I worked with Martin Kruskal quite a bit, with John Greene somewhat less, and with many people who visited Martin, like Norman Zabusky, Mark Ablowitz, and others. Working regularly with Martin Kruskal over extended periods of time was a high point of my scientific career. I learned an enormous amount about mathematics from Martin Kruskal.

While I was working in Princeton, what is now the Kavil Institute of Theoretical Physics, at the University of California at Santa Barbara invited Martin Kruskal to direct a Program on Integrable Models, which would run over several months. (An objective of this Institute is set up to run such programs, each focused on a specific aspect of theoretical physics.) Martin enthusiastically accepted the invitation, and he deputized Mark Ablowitz and me to be co-directors of the Program. It was exciting, because many scientists, working on this topic, were able to meet each other, often for the first time, and to discuss aspects of this topic, face-to-face. I think that everyone learned from these many interactions. In addition, Santa Barbara is a very nice place to visit. Our family spent one delightful year in Santa Barbara, before returning to Princeton.

- **Around this time you and others in North America started to interact more with Russian scientists.** Meeting with Russian and other scientists "behind the Iron Curtain" was very interesting. I remember two meetings, one in Warsaw, Poland and the other in Kiev, Ukraine. The one in Kiev especially stands out, because some Soviet scientists were not allowed to travel as far away as Poland, but the Ukraine was considered "safe" enough to allow various scientists to travel that far from Moscow. The Kiev meeting was an official US-USSR scientific meeting, and I think that it was the first one of its kind.

  The scientific aspect of that meeting was interesting and useful, but the opportunity to meet for the first time with people whose papers I had read and studied carefully was the high point of the meeting. The cultural differences between the two groups was noteworthy, in many ways. For example, one day during the Kiev meeting, Mark Ablowitz, Sergei V. Manakov, Sasha Mikhailov and I were in a classroom in the building where the conference was being held. Manakov had mentioned to me in some earlier conversation that he was a fan of the writing of George Orwell. I asked him who his favorite authors were; he looked at me, he looked up at the ceiling, he looked at a small sink on the side of the room, then he raised his eyebrows and changed the subject. I understood that he was signaling to me that it was not safe to discuss such matters in that room. Wow!

  In a different conversation, elsewhere, he said how impressed he was that an English writer like Orwell could simply imagine what it is like to live in a police state, like the USSR. (I think that he had Orwell's 1984 in mind, but he didn't say.) Manakov was my favorite Russian scientist. Unfortunately, he died some years ago.

- **Next, you joined SUNY Buffalo.** After we returned to Princeton, it was becoming clearer that the company in which I worked was changing, partly because the founder of the company was considering retirement. About that time, I was offered a position in the Math Department at SUNY Buffalo. There were good things and not-so-good things about the Math Department at SUNY Buffalo. It turned out that the department there was not a good fit for me.

- **How did you end up in Boulder?** After I had left Clarkson, Alan Newel also left, to take a position at the University of Arizona. Mark Ablowitz had become Chairman of the Math Department, and then Dean of the College of Arts and Sciences. In addition, Mark had taken up flying, and he was the part owner of a 2-engine plane. While we were in Buffalo, Mark, his wife Enid, and their son, Todd, flew from Potsdam to Buffalo to talk to Carol and me. Mark had been offered an opportunity to create a new Department of Applied Mathematics on the Boulder campus of the University of Colorado. He wanted to know if I was interested in helping to start this new department.

  It took me about 3 minutes to make up my mind. CU Boulder was well known for its Physics Department, its Molecular Biology Department, and others. This sounded like a great opportunity, Carol was thinking along the same lines, and we agreed. The mountains and hiking were a great attraction.

- **Tell us about your time (so far) in Boulder.** Boulder is a nice place to live. The natural setting of Boulder is wonderful, in my opinion. (Ignore the fires that have been burning in Colorado for the last several months.) Another feature of Boulder is that CU has some very strong departments in the sciences and in engineering. Often it is easy to talk to people in these very strong departments. Generally, there are many friendly people in Boulder, and at CU.

  For the last 5 or 6 years, I've been teaching a one-semester senior-level course in partial differential equations. This course is required for applied math undergraduate students, but usually the course has an enrollment of 80-120 students, in 3 sections each year. Year after year, there are remarkably good students in this class. Some are applied math students; some are not. I enjoy having very good students in the class, and over the years I have been very impressed with how many good undergraduate students there are in the Applied Math Program.

- **Any advice for young people interested in nonlinear PDEs?** Perhaps: *follow your own interests*. As spelled out above, I got into integrable systems by a sequence of decisions that were not necessarily based on careful planning. Even so, it came out OK. Maybe that was pure luck.

  On the other hand, when I first met Gelfand, I was about 30 years old. He asked me something like: What is my main objective in mathematics? I was surprised by the question, because at that time, I had no master plan for my scientific journey. So I asked him if he always knew what he wanted to accomplish during his scientific career. He was ready with his answer. In fact, he had set me up. He told me that when he was about my age, he sat down and looked at the big picture in mathematics. So he picked three different mathematical problems that were unsolved and of interest to him. Then he named the three problems; each problem was a problem that he had solved during his long career. I was impressed, because I had never heard of such foresight.

- **What problems are you working on now?** Wind-driven waves. These are also part of the family of water waves, but they apparently have no relation to the wavetrains that are usually studied: a train of periodic waves, or a train of dispersive waves, which are approximately periodic. In nautical lore, waves that propagate on the air/water interface, are classified as swell, like waves that are generated by a large storm on the ocean surface, and that propagate away from the storm, versus seas, where the waves are often irregular and driven by the winds blowing above the air/water interface. Each of these two kinds of waves can be seen by watching the waves that propagate on the surface of a body of water.

Thank you very much for taking the time to have these conversations with us!

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