Chaos at the Table

In Memoriam for Henry D.I. Abarbanel

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[1] https://dsweb.siam.org/The-Magazine/Article/chaos-at-the-table

Henry Abarbanel's research students had a saying: "If you can survive presenting at a group meeting, you can make it as a physicist."

That's what I, as a postdoc, hastened to explain to a bright-eyed first-year graduate student who dropped into our weekly meeting one day in fall 2015. A visiting faculty member was presenting his work on estimating parameters in a dynamical model of a neuronal synapse in the avian brain. Henry was snoring. Suddenly he awoke and sat bolt upright. "But why did you choose this particular model?" he asked the presenter. "How does this model best represent the available data?" The presenter did not have an answer. As always, when Henry felt the question was important, he wouldn't let it go. Especially as he saw that not all of us grasped *why* the question was important.

A curiosity-fueled bloodhound, Henry redirected his question from the presenter to a student. Then to another student. Then soon to all of us, never noting the ever-reddening tinge across the presenter's cheeks. For a while it was chaos, albeit chaos controlled by Henry's canny – and *un*canny – driving force. Eventually, we collectively froze out a plan toward the answer, and Henry found it an acceptable note to end on. A typical group meeting.

But I feared the impression made on Sasha Shirman, this research-group-shopping graduate student. "He didn't mean it that way!" I blurted after we'd left. "He's not trying to embarrass anyone – he's just after the answer." Sasha grinned. "Also the process?" I grinned back. Yes, the hunt. "Don't worry, I'm in," she assured me. "I mean, yes, he's kind of scary. But *good* scary."

FIG. 1. Henry ("Professor Zucchini") and granddaughter Joanna ("JoJo") at JoJo's third birthday party, April 2023. *Courtesy of Brett Abarbanel.*

I. Henry's path integral

Henry Don Isaac Abarbanel was born May 31, 1943, in Washington D.C., and at age two moved to Southern California – a locale that throughout his life he would call "the best place to live in the world." He skipped several grades, and earned his B.S. in Physics from the California Institute of Technology at age 20, and at 22 a PhD in Physics from Princeton, with work in particle physics and quantum field theory (QFT). Early close collaborators were Robert Sugar, John Bronzan, Alan White, and Joachin Bartels. Robert Sugar, who became a lifelong friend, describes Henry's early interests as "broad," and that he did not find utility in traditional disciplinary boundaries.

Henry's CV [1] is dizzying. Upon skimming it, one's impression is of discontinuous jumps from topic to topic, in no clear order. On examination, however, a path emerges. He may not have known at the time where each step would lead (one can predict – but not *know* – the future), but the steps all had purpose.

Fluids, nonlinear dynamics, chaos, and control

Following his PhD in 1966, Henry spent 17 years in a myriad of invited positions around the globe. These included multiple particle accelerator facilities, as well as many visits to dynamicists in what was then the Soviet Union (USSR).

His first discipline-leaping move, in the early 1970's, was bringing the renormalization group – a tool developed for particle physics – to bear upon fluid dynamics. Also around that time, he encountered the dynamical

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systems framework for understanding nonlinear behavior. William Bialek, who had been a graduate student at UC Berkeley when Henry was briefly a lecturer there (1980), recalls that Henry was an ever-present figure and "taught unusual classes." His first published work on nonlinear systems was a series of such lectures: "Dynamics of non-linear stochastic systems," 1978 [2], in which he employed a potpourri of examples including QFT, wave propagation in various media, fluid flow, and radar.

Henry was particularly taken with the notion of chaos. That a deterministic system can intrinsically exhibit chaotic behavior "gave me both great pause and great relief" (preface to *Analysis of Observed Chaotic Data*, 1996 [3]). The relief came as chaos presented an explanation for turbulence in fluids, a problem he had been wrestling with. And "the great pause came from not knowing what to make of chaos." The quest to understand the functionality of chaos, and to predict and control it for practical purposes, would become a theme of his career.

In 1983 Henry began a joint appointment with the Scripps Institution of Oceanography and the University of California, San Diego (UCSD), a position he would hold for the rest of his life. Within three years there, he founded the Institute for Nonlinear Science (INLS). He invited in representatives from fluid dynamics (Jon Wright, Michael Longuet-Higgins, Evgeny Novikov), biological physics (Herbert Levine), pattern formation (Cliff Surko), statistical mechanics (Katja Lindenberg), and biology and neuroscience (Allen Selverston), to ferret out fundamental principles across dynamical systems in nature. Katja, who was Vice Chair of the INLS throughout its lifetime, notes, "Henry was instrumental in the creation of the INLS. ... He gathered the people that became part of it. At the beginning there were Nonlinear Institutes at other UC campuses and Los Alamos with very dedicated people, but Henry certainly had a big hand in all of them. He was visionary in this; I don't know of any such programs that existed anywhere else at that time." He would be the INLS director from its inception (1986) through 2007.

With Reggie Brown and Matt Kennel, Henry furthered existing geometric methods of characterizing the nonlinear dynamics giving rise to measurable quantities. They developed a new means of identifying "false nearest neighbors" to determine the minimum local embedding dimension required to capture such dynamics. This Henry saw as a critical starting point for model-building; that is: identifying the number of degrees of freedom required to faithfully characterize it. Henry wrote, "If one wants to build models of the observed system, then working in the minimal number of dimensions, namely d_L, will reduce the amount of work in establishing and verifying that model as well as reduce its sensitivity on noise which would occupy without any dynamical significance any dimension offered it" ("Local false nearest neighbors and dynamical dimensions from observed chaotic data," 1993 [4]).

Especially influential in his work on nonlinear dynamics were his visits, beginning in the 1970's, to dynamicists in the USSR. These included Vladimir Gribov, Misha Rabinovich, and Lev Tsimring. Lev met him in 1990 when he and Herbert Levine visited his then academic home, the Institute of Applied Physics of the USSR Academy of Sciences on the invitation of Misha Rabinovich, the head of their research group. At the time, Misha's group was well known in the West for contributions to nonlinear dynamics, fluids, and chaos theory. Lev recalls, "The Soviet Union started to open up to the world thanks to Mikhail Gorbachev's policies ... and Henry was one of the first American scientists who saw this as an opportunity to establish new contacts ... especially in physics, which was well known as the field where Soviet science particularly excelled." He adds, "Henry was fascinated by the idea of learning about dynamical systems directly from data these systems were generating. For linear systems, it was a well-trodden gound, but Henry was interested in nonlinear, furthermore, chaotic systems, where classical tools simply would not work."

In the mid 1990's, Henry invited Lev and several other Russian scientists to make a permanent move to the INLS. Henry, Lev, Nikolai Rulkov, and Misha Sushchik then together studied synchronization, the mutual adjustments of the rhythms of two distinct oscillators. They introduced the notion of "generalized synchronization": the case of weak coupling between two non-identical chaotic oscillators, and developed the method of "mutual" false nearest neighbors to identify such a scenario.

The myriad of publications and lectures that came out of this era are collected in Henry's 1996 book, *Analysis of Observed Chaotic Data* [3].

Biological neurons

It was at the INLS where Henry became intrigued with biological neuronal networks. At the time, Allen Selverston, an experimental neurobiologist Henry had invited there, was studying the stomatogastric ganglion of the lobster. This structure contains roughly 30 neurons that comprise two overlapping central pattern generators (CPGs) that drive the muscles for chewing and swallowing. Henry and Al began a collaboration. Years later Henry recalled, "The idea was that if one side of us could explain our joint work to colleagues on the other side, it might generate a new set of collaborations among neurobiologists and physicists. These many years later, collaborations such as we had envisioned are part of

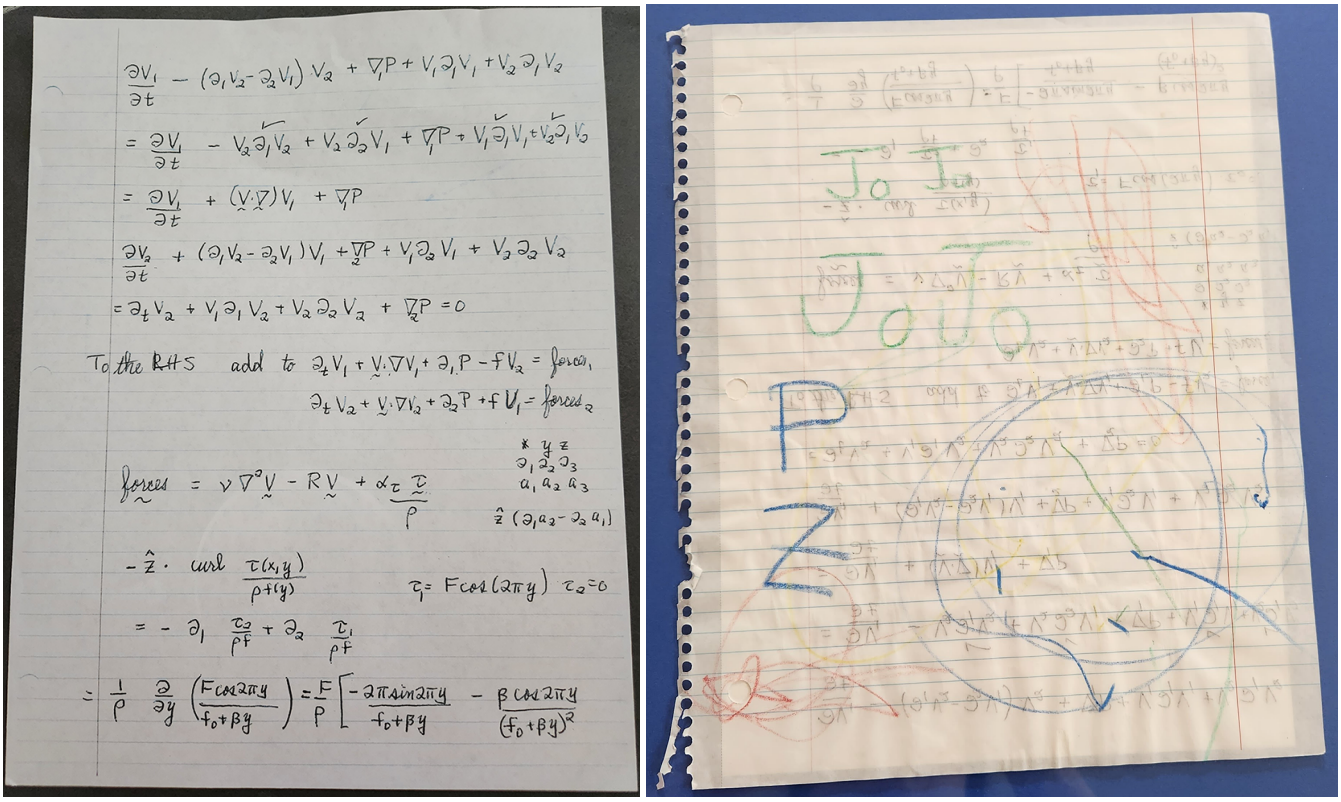

FIG. 2. *Left*: A page of Henry's notes. *Right*: The back of these notes, on which he taught Granddaughter JoJo to write her name, as well as abbreviate the name she'd given him ("Professor Zucchini"), spring 2023. *Courtesy of Sara Abarbanel.*

academia writ large. Alas, we can hardly take credit for that very satisfying outcome" ("A personal retrospective on the 60th anniversary of the journal Biological Cybernetics," 2021 [5]).

Lev Tsimring recalls that period: "When he saw an opportunity to apply nonlinear dynamics to neuroscience, he changed the focus of the whole Institute in a matter of months, convincing many of his collaborators to join him in that new direction, striking new collaborations, re-focusing his students, bringing new postdocs and visitors. And it worked: the INLS became one of the premier centers for nonlinear neuroscience in the world." A former student, Owen Curtis, articulated well Henry's grasp of the great strength in cross-disciplinary collaborations: "how instinctively he knew that ... it would be wisest and easiest to team with those in other fields, and cross-fertilize their efforts." One connection he made in that respect was using Misha Rabinovich's "winnerless competition" dynamical framework toward understanding the mutual inhibition displayed by Al Selverston's neurons.

It is not hard to imagine why Henry was attracted to the neuronal CPG. In prior work on synchronization, Henry had employed as example data the output from human-made electrical circuits. Now, here was an autonomous *biological* electrical circuit. Does Nature build smarter circuits than people do? (Yup. In later years this would tie to his work toward building smarter artificial intelligence (AI).) Further, each CPG neuron possesses a remarkable property that – I speculate – intrigued Henry: when isolated from its circuitry, it can exhibit chaotic dynamics. Yet when wired together, the chaos vanishes. *Collectively*, the neurons communicate so as to produce a robust, highly stereotyped patterned output that underlies the organism's survival. From chaos emerges order! So chaos is being harnessed to establish stability. ... How so?

Bird brains and data assimilation

A tantalizing step beyond the crustacean CPG: neurons that can *learn* to communicate. Henry was introduced to these by yet another invitee to the INLS: Gabriel (Gabo) Mindlin. Gabo was a dynamicist based in Argentina, and had caught Henry's attention for building dynamical systems based on a type of time series data that, to Henry, was novel: birdsong. Most birds are born producing relatively simple vocalizations. Others produce more complex sounds called songs, and in most of these species the song is learned. Birdsong learning is widely viewed as the premier vertebrate system for studying vocal learning.

At the time Gabo joined the INLS, in 2002, he had

published rate-based models of the songbird system (e.g. Wilson-Cowan oscillators). With the aim to build stronger collaborations with experimentalists, Henry suggested that Gabo extend his work to more detailed realistic models (i.e. Hodgkin-Huxley). Those he thought would allow for better comparisons with experiments and garner more attention from biologists. He and Gabo worked together on this effort.

Soon after, Henry met Daniel Margoliash, an experimental neuroscientist at the University of Chicago, who was studying song production in birds including zebra finch. The male of this species learns a highly stereotyped song from his father, and uses it to attract mates. The zebra finch vocal system is the most extensively studied of all songbirds, due to various advantages they offer for the laboratory setting. For this reason, Henry would come to call the zebra finch "the hydrogen atom of language learning."

After discovering Dan's zebra finch in 2003, Henry invited him back the next year to lead a summer school on birdsong. The two visited frequently thereafter, and Henry began modeling HVC, a neuronal nucleus implicated in the song production. His dedication to this effort included visits worldwide, notably several to Richard Hahnloser, who was using a combination of theoretical and experimental approaches to study songbird vocal learning and imitation.

Around this time (the mid 2000s), Henry found data assimilation (DA). DA is a statistical tool developed for numerical weather prediction, to complete and test dynamical models based on data. His discovery of DA may have arisen out of his existing connections at Scripps, and/or to his involvement with SIAM beginning in the early 2000s. Or it could have led naturally out of his work on synchronization and control. Regardless of how he came upon it, he rapidly recognized DA as a *communications problem* – and that it could be tailored to provide a *means to test* models of biological neurons and networks.

In the preface to his second book, *Predicting the Future: Completing Models of Observed Complex Systems* [6], Henry described his motivation for expanding DA to handle noisy neuronal data: "This monograph arose from my significant confusion about how to understand nervous systems as a physicist ... The point of view presented ... is to view as a communications and dynamical systems problem the general challenge of transferring information in observed data to a physical ... model of the system producing those data." And: "The other theme in our formulation of DA is that of potential instability in the communications channel between the data as a transmitter and the model as a receiver. This is a feature of the nonlinearity of the models." Henry's unique formulation of DA was essentially in the casting of the problem. Namely: which, and how many (and for how long, etc.) measurements are required to estimate model state variables and parameters for a prediction of satisfactory strength?

Henry's harnessing of a weather prediction tool for predicting noisy neuronal dynamics happened over just a few months in 2009. First he found a paper written the year prior that set forth a path-integral formulation of DA. This approach probably appealed to Henry as a physicist: that the driving of a model via real measurements could arise naturally via considering a path in a state space on which an action is extremized. Henry expanded this formulation for use with real data, importantly allowing for imperfections – namely, noise in measurements. Then he showed up with it to Dan Margoliash's lab, and asked Dan to try out some new experiments.

Dan recalls, "You know that picture of Henry smiling next to the rack of equipment? He told me that he was smiling because that was the closest to a piece of equipment he was ever allowed to approach." He and Dan would go on to collaborate as an experimentalist/theorist duo for the rest of Henry's life, and as good friends.

One important discovery he and Dan made was identifying the waveforms of experimentally injected currents that yielded reliable parameter estimates of neuronal electrophysiology. Henry's fascination with the utility of chaos enters here. By now he had developed a conjecture for why those CPG neurons will, when isolated from the circuit, exhibit chaotic behavior. In *Analysis of Observed Chaotic Data* [3], he wrote, "that the ability of a system in chaotic motion to explore wide regions of its phase space, and thus utilize information about a large collection of potential states of the system [is an evolutionary advantage]," and that "biological systems that do not take advantage of chaos in their state spaces may not be able to participate in evolution to the extent we understand that as adaptation to changing environments. Of course, we are unlikely to see such systems as they are now extinct."

So Henry suggested that Dan force his neurons to explore. Namely: replace the traditional (step and periodically varying) stimuli with chaotic waveforms. This change would drive the state variables through their full dynamical ranges – ranges they may rarely need but should still know about. (Or consider an athlete who stretches prior to performance, even though the sport itself does not call for such outlandish postures. A stiff athlete will probably lose.) Indeed, this substitution resulted in significantly more stable parameter estimates of cellular properties. A DA practitioner might describe this result as the chaotic component facilitating more efficient information transfer from measured to unmeasured degrees of freedom.

Smarter AI and data-driven forecasting

Henry always had his hand on the pulse of how information was being used (or rather exploited?), in academic science as well as society at large. His work on testing models of natural biological circuits seems to have led naturally to his interest, beginning around 2018, in harnessing data from those circuits to devise more power-efficient AI.

We shouldn't be as impressed as we were, he liked to tell us, by the advent of computers that could beat a biological human brain hands-down in a game of Chess. "To beat your brain, that AI requires 10,000 times the power," he would say in a slighting tone, reminding us that current AI is neither informed – nor even inspired – by real biological circuits. "Clearly, Nature has a smarter idea." With the aim to ferret out that idea, Henry co-founded the Center for Engineered Natural Intelligence (CENI), along with UCSD colleagues Timothy Gentner (in Auditory Neuroscience; specifically birdsong), and Gabriel Silva and Gert Caughwenbergs (in Engineering). CENI aims to design AI circuits based on data from the neural avian vocal center associated with language learning and production. Henry's former student Owen Curtis recalls a recent discussion with him: "He was looking to clarify the difference between true AI and machine learning (ML). He related it to his work on how a baby bird learns to sing its own species' song, and not the song of another species."

Toward that end, in 2018 Henry began exploring the relationship between DA and ML. He initiated contact with those in industry, including a colleague of Gabriel Silva's who was running a research group within the Special Projects division at Microsoft. That group was interested in the potential of DA to inform ML for optimizing network architectures. Those conversations did not develop into a collaboration, but they informed his research. His third book, *The Statistical Physics of Data Assimilation and Machine Learning*, 2022 [7], details this work.

Most recently, and with his newest generation of graduate students Randall Clark, Luke Fairbanks, and Lawson Fuller, Henry had shifted from DA as it is traditionally defined to "data driven forecasting" (DDF). DA and DDF share the same paradigm. DDF, however, is based more purely on measurable data, less so on an associated model in which unmeasurable quantities also exist. Henry's approach to DDF does so by employing time-delayed versions of measurements as stand-ins for unmeasurable quantities. This time-delay formulation, attributed to Ruelle (1979), rests on the notion that one can represent a dynamical system in N state variables, or equivalently one state variable sampled at N discrete times. A pillar of nonlinear dynamical systems theory, the notion is intimately related to the information contained in the derivatives of a time series.

To develop this DDF paradigm, as usual he had his students working on multiple distinct systems, including the "shallow water equations" (a simplified Navier-Stokes system), Earth's magnetic dipole, and, of course, biological neuronal circuitry underlying intra-species communication.

Government and public service

Henry felt a strong sense of responsibility to his community at large, and that – as a scientist and communicator – he could be impactful.

In 1974 Henry joined JASON, a team of scientists who advise the federal government on matters of science and technology. Most of his work with them appears to be still classified, but one important declassified project is early work (1980) on climate change [8]. Henry remained active with JASON throughout his life.

In 1989 Henry became a public servant in his home city of Del Mar. After first serving on the local Planning Commission, he became an elected member of the city council from 1992-1996 (mayor from 1995-1996), and again from 2000-2008. In 2011 he joined the San Diego Regional Water Quality Control Board, working fiercely – and to great success – to improve water safety regulations in San Diego County. Former colleagues ascribe his success in the public arena to his "nonlinear thinking."

Lauraine Esparza, who was city manager during Henry's tenure on the council, recalls, "He would come up with outlandish ideas, the kinds of things that make you roll your eyes." For example, many of Del Mar's residents had retired from impressive professions: some venture capitalists, one former head of the Federal Reserve – and Henry suggested inviting them to join the city finance committee. "What?" That those accustomed to juggling billion-dollar sums would be interested in pitching in in Del Mar? "Why not?" Henry would challenge. "The fact that we were the smallest city with the smallest budget and the smallest population did not daunt him at all," Lauraine says. "Henry was absolutely confident new residents with impressive personal credentials would be *pleased* to serve on a city board – he held public service in that high a regard. So he would ask, and often they would accept, and end up making lasting contributions."

Driving force

Henry's brilliance and inventiveness, and the impact of his work, were only part of what made him an admired scientist and public servant. Beyond that, Henry had a spirit that inspired others to rise to the occasion.

Back to our group meeting in the fall of 2015 with the embarrassed presenter: he was embarrassed because Henry had (inadvertently?) laid bare to him that he could have done better. A few weeks later, that presenter in fact returned, eager to share what he had learned since we'd last seen him. He could now offer a well reasoned argument for using the model he was using, and he thanked Henry for having been "so annoying" with his line of questioning. In addition, Henry had (inadvertently?) used that group meeting to remind the rest of us that we can always be digging deeper.

Students 50 years his junior were confounded by Henry's drive. We would receive emails from him at all hours of the day and night, leading some to swear that he never slept. But that wasn't it. In fact, and in his daughter Brett Abarbanel's words, he was a "champion sleeper." He simply slept strategically – and loudly – through faculty meetings, physics colloquia, and generally at times when he figured he wouldn't be getting any work done anyway. (Further, he was known for waking suddenly to ask a pointed question regarding what had been said whilst he'd been snoring.) But snooze through a perfectly usable calm quiet night? Sacrilege.

In the spring of 2023, Henry was intently batting a manuscript draft back and forth with his graduate students on the new DDF paradigm. In April he met with a former Del Mar city manager to brainstorm new ways of tackling residents' quality-of-life concerns. A few weeks later, Henry buzzed about taking candid photos at the day-long third birthday bash for his granddaughter Joanna (JoJo); see Fig. 1. On May 23, he and his wife Beth Levine returned from a three-week vacation to the Canal du Midi in France and the Spanish Pyrenees. On the morning of May 26, Henry purchased a flight to New Zealand, a favorite peaceful spot where he planned to begin writing his fourth book. Hours later he was gone, five days shy of his 80th birthday, having rarely – if ever – wasted a night sleeping.

II. Henry's table

It was clear to those who knew him - even those who simply read the preface to one of his books - that the roles he valued beyond all others were as husband to Beth and father to Brett and Sara. Luckily for the rest of us, he extended the spirit of family to his friends and respected colleagues (and at times even to respected adversaries). Meanwhile, all his work described above – particle/field interactions, nonlinear dynamics, chaos, synchronization, control, data assimilation, neuronal circuitry, birdsong, AI, public service – shares a theme: communication.

At Henry's memorial service, Beth recited a poem she had written on the occasion of his 50th birthday 30 years earlier. In it she spoke of a table. A long wide plain wooden table Henry had acquired while living in a commune in Palo Alto in the 1970's. He brought it to Berkeley during a brief run as lecturer (UC Berkeley) and staff scientist (Lawrence Berkeley National Lab) in the early 1980's. Beth recalled, "We met over Scrabble at that famous table; we then got married as soon as we were able." When the two moved down to Del Mar in 1983, so did the table: "The table persisted in having a force; it determined the size of our house here, of course." And throughout the next 40 years, it was to serve as a joyous and powerful communications pathway.

For problem solving

Henry hit upon his suspicion regarding chaos' utility – that is, to enhance an organism's competitive edge – rather quickly after encountering it. His intuition here may have come from his experience that that kind of exploratory behavior is precisely the recipe for effective communication and problem solving, in life in general.

Claire Max, a colleague, mentee, and friend with Henry on JASON, noted his approach that was so effective in tackling problems of government interest: "He brought everybody together." He would convene members "with competing opinions" in a room, and start a discussion. At the start there could be heated disagreement about how to solve a problem; it might not even be clear what the problem even *was*. Often Henry would bring "the JASONs" to his home, to debate and brainstorm around his own table. Claire says, "He enjoyed bringing together newer JASONs and long members, sometimes at home or [at a] local restaurant." He would listen intently, always open to any idea so long as it was reasoned and proposed in good faith – but "he did not suffer fools."

He would fold in friends and family. His neighbor and longtime friend Harold Feder recalled at Henry's memorial service the time Henry invited him – a person with zero scientific training – over to meet the JASON crew. Simultaneously delighted and intimidated by this elite company, he was mystified by why Henry had invited him. Later he realized, "He wanted me to understand *why* he loved these people, why they were so important."

Lauraine Esparza recalls stories of a similar theme. Henry was on the council that hired her as city manager in 1992. As an elected official, Henry's job was to help solve the problems of his local community as well as those of greater San Diego, which involved peripheral entities such as the water quality control board.

Lauraine recalls, "Henry was not constrained in the way so many people – including myself – are: linear thinkers. The fact that he specialized in chaos theory

I think has something to do with the way he thought about the world and problem solving." She goes on to describe this approach: "Henry's process involved bringing people together, to brainstorm, do research, collaborate, and come up with multiple solutions. He was very good at building bridges."

As with the JASON crew, Henry parlayed his Del Mar city council role into enriching experiences for family and friends. One morning he announced to Lauraine, "You have a speaking opportunity. I've booked you into Brett's third grade class, to talk about city government." She was startled, but could offer no comeback to his "Why not?" challenge. So she went, and talked with the children about the important actors in their home town – lifeguards, firefighters, garbage collectors. "It was really quite fun ... It's the only time in my 35 years in public service that I ever spoke to a third-grade class about city government."

At times Henry's adversarial side would emerge. "He had trouble with fools," Lauraine says. "If you proceeded ... with an honest spirit of inquiry, Henry would be great. But if he thought you had a point of view and an axe to grind, he could demolish your point of view if he chose to. If he thought someone was deliberately obfuscating or not seeing the truth of a thing, he could be arrogant and rude." Beth notes, "Henry was very much a free spirit who had his own sense of what was right." And pity the person who crossed him on it.

At the same time, Lauraine says, "He was also very modest. If you didn't know that you were meeting with a brilliant scientist with a reputation, that you were just meeting with a council member from the city of Del Mar, you wouldn't have any idea who you were really dealing with. And then he would surprise people."

One particular bridge Henry set out to mend was the then-caustic relationship between local city managers and the San Diego Regional Water Quality Control Board, or "water board." This agency sets standards of compliance for protecting the area's waters, for example, the frequency of testing. The city staff did not oppose the regulations; rather, they opposed the rigidity with which they were enforced without appreciation for the practical timescales involved in implementation. Or, the cities and the board designed to protect them were out of synchronization.

And what was Henry's solution? He joined the water board.

David Gibson, who at the time had recently taken over as their Executive Officer, says that joining the board was a nontrivial feat. "Henry would have applied to the governor for the appointment," he says, "and would have had to submit a substantial amount of financial information and participate in ... interviews with the governor's appointment office." So clearly he joined with ferocity.

And he joined as a ferocious critic. Dave acknowledges that this was understandable given his predecessor's legacy of rigidity, and that Henry "bristled at authoritarianism wherever he saw it." But "one of the things, to Henry's eternal credit, which you see so seldom ... in people, was that he was willing to acknowledge and review his own biases, and if they were incorrect or poorly informed, he was willing to change them."

"He came in and he asked questions," Dave recalls. "He saw it as his role to bring board members together ... he wanted to understand why we were doing what we were doing." And he listened. "He was absolutely willing to talk with anyone who came up to the podium during the board meeting." And "It took him a few months to realize we were doing things differently than ... before, ... that the water board was ... more what he wanted, more transparency, more public involvement/engagement, more focus on environmental justice issues, neglected neighborhoods, climate change." Once each of them recognized in the other the same focus on environmental outcomes rather than bureaucratic process, they became strong collaborators. Within a few months "he went from being one of our strongest critics to being one of our biggest cheerleaders ... impressed by the quality of the science that was being done by [regulators] who don't get paid to be scientists."

Naturally Henry roped in his graduate students – some of whom, incidentally, were applying DA to the shallow water equations. He brought them to board meetings, and on visits out of the city to examine the communications routes with the larger entities involved – to ascertain whether the board had the required support from governing structures to effect real change.

A recent resolution from the board honors Henry's memory: "The Members of the San Diego Regional Water Quality Control Board honor Henry D.I. Abarbanel for his meritorious service to the public; his dedication to improving science and technology; and his steadfast commitment to the public service in the development of sound public water quality policy." Dave is confident that the board will continue in the direction Henry has pointed it: "My conscience carries a heavy Henry imprint."

What a strategy for problem-solving. Dive into a mess, ask annoying questions, listen, sometimes be stubborn, sometimes be wrong, learn. The reader might note that, while this article has given "chaos" abundant context, it has not offered an explicit definition of the term. I like to think Henry would leave that as an exercise. As his daughter Brett so aptly and lovingly phrased it at his memorial service, Henry was "a delightful and purposeful pain in the ass."

For community

As a mentor, Henry was devoted. Beth notes, "He regularly did not take the full amount of summer salary (and sometimes didn't take any) so that he could use those funds to pay students." In a tribute at Henry's memorial, friend and neighbor Harold Feder noted, "I see many of Henry's students here, and I think it speaks to their love and admiration and respect ... Henry truly loved his students, and it seems that his students truly loved him."

Owen Curtis was an undergraduate in the first class Henry ever taught, at Princeton in 1968. He recalls the interest Henry took in him and his peers, which was unusual for faculty: "He wanted to know what we, the students, were thinking and learning." And he delighted in making the learning fun. A three-hour lab on momentum, for example. "Out of the back room came Henry, with his arms full of .22 rifles. 'Gentlemen,' he said, 'today we are going to learn about momentum ... And how or why this University thinks it is safe to mix rifles and 18-year olds indoors is beyond me, but please, let's prove that they are correct.'" Owen notes that Henry's enthusiasm for teaching blazed just as strongly many years later. Recalling a recent interaction the two had had: "One of the great aspects of a conversation with Henry was how he could describe the complex nonlinear work he was doing by relating it to something that anyone could grasp."

In 2022 Henry supported those who participated in a UC-wide graduate student strike, even though it meant research would slow to a crawl. Luke Fairbanks recalls, "When we were explaining the situation to him in terms of the quality of life of student workers he quickly understood our struggle and gave the green light for us to participate. The strike has led to a massive change in our workplace protections, financial stability ... He went on to welcoming a student into the lab, Daniel Primosch, who had a falling out with his old advisor due to retaliation for striking."

Henry's female colleagues note his support for women, through times when that attitude was far from the norm. Claire Max recalls joining JASON in the early 1980's as their first female member: "He was particularly kind to me," and encouraged her to stay through some treacherous episodes. Katja Lindenberg recalls joining the INLS around the same time: "I was one of only two female faculty in my department and no one had the kind of environment I had, in no small part due to Henry. He never ever made any point about that, it was all just very natural." She accompanied him to the USSR during the 1990's, where she was welcomed as the first Western woman many had ever seen. I recall Henry's reaction once to derogatory comments about women that had recently been made on campus by a high-profile person. He listened to us recount the story and shook his head: "This guy who calls women 'weak,' I don't get it. He should meet my *daughters.*" His eyes gleamed. "My daughters could level you. And they don't need a gun or a bicep – they can do it with a *sentence.*"

Henry extended his community spirit well beyond his own SoCal abode. Lev Tsimring recalls Henry's first visit to their group in the Soviet Union in 1990: "He wanted to meet every member of our lab ... and he suggested that we sit down and do some simulations together. 'What, right now?', I said. 'Sure, why not?' answered Henry. ... I remember him sitting for hours and hours listening ... and trying to understand our very broken English (which he called 'Russish'), asking a myriad of probing questions, cracking jokes, telling stories ... his uncanny ability to break through artificial barriers and get straight to the point was something that I observed in him so many times later on."

Lev goes on to say, "Henry ... affected my life in the most profound way," referring to Henry's pivotal role in Lev's relocation to the U.S. and permanent position at the INLS. And beyond that, Henry treated Lev's family as his own. "We came to the U.S. with virtually no money ... So the first thing he did ... he took us to a supermarket and bought a whole cart of food to subside on in those first days. He took us whale-watching. He lent me the money to buy our first car. He welcomed us into his home for many memorable evenings. 'I'm a Jewish mother,' he liked to say. And I was only one of many whom he brought to UCSD and helped to settle and launch a new life and a successful career." Those others were: Mikhail (Misha) Rabinovich, Nikolai Rulkov, Alexander Volkovskii, and Mikhail (Misha) Sushchik.

Gabo Mindlin had a similar experience. "One important aspect of Henry's life was helping scientists going through rough times," he says. "So, when Argentina went through the meltdown and political crises of 2002, Henry wrote to me inviting me to go to UCSD ... I arrived in the U.S. with my family and 35 dollars. I had sold the car to get my tickets. So not my happiest moment. I guess that is what led Henry to invite me almost every Sunday that the San Diego female soccer team played in SD to see the game."

Gabo also notes, "Henry was not the easiest person to interact with, but he was extremely generous, in a non obvious way. He would never make public what he would do for others, but for many people facing real problems, he was there, and he did offer real and meaningful help. The year I was in San Diego, I learned to write grants for the NIH, and that had a huge impact on my career, and of course interacting with him was fun."

Henry's deepest devotion was to Beth, Brett, and Sara. A family friend, Beth Jay, recalled at his memorial service having introduced Henry and Beth in 1981. "Henry

always supported his family. ... their independence, ... their curiosity, supported whatever they wanted to do. He was there. ... And he might argue with them. But he was there for them every step of the way. ... They were such a strong unit together; it was just lovely to see." She also reminisced about the many parties, themed dinners, and games that took place about that massive table.

Often during our group meetings, Henry would segue into a family story. With reverence he would recount Beth's latest globetrotting adventure, which often required some athletic feat such as skiing (hence his having begged out). He recounted questions his daughters had posed over the years (e.g. Sara around age six wondering why North Korea wanted "unclear" bombs). He proudly recalled refusing to answer a question directly, instead milking it as an opportunity for exploration: "Let's figure it out together." Brett confirmed this in her heartfelt memorial speech: "He taught me the fine art of asking questions. He would spend long hours with two-year-old Brett, sounding out the words 'til I could read all the books on my own." Even more proudly, Henry would describe to us what lessons his daughters were now teaching *him*.

The interactions that delighted Henry most in recent years were those with his precocious granddaughter JoJo. At 16 months, JoJo could use the palms of her hands to demo kinetic friction. "Now do angular momentum!" he challenged. In March 2023, shortly before she turned three, JoJo asked her PZ ("Professor Zucchini" was her name for him) what wind was. Turns out this was one of the questions Henry's PhD committee had asked him at his defense in 1966. He paused a conversation he was having, turned his full attention to JoJo, and expounded on a lengthy description of Earth's rotation, the Coriolis effect, and atmospheric circulation, omitting nary a detail. JoJo listened attentively. Then she reflected for a moment, and said, "okay."

Finally, a personal story of Henry's playful warmth and generosity. When I joined his group in fall 2014, he knew I was 3000 miles from my family back East. He invited me for Thanksgiving at his home, with Beth, Sara, and neighborhood friends. My husband Wayne flew in. Henry had not met him, but knew from me that he liked to bake. Upon our arrival at their door, Henry had made a luxurious spread across that well worn table of eggs, flour, butter, and apples – and invited Wayne to make a pie (alas, at the time I knew nothing of the table's impressive storied past). "Now?" Wayne asked, startled. "Why not?" came the reply. "We have an hour 'til dinner." So Wayne got to work. When it was done, Henry invited me to carve into the crust Maxwell's equations – a set of coupled partial differentials that underlie classical electromagnetism. I managed to fit in two of them. He surveyed my handiwork, and Sara watched him with amusement in her eyes. I looked at her questioningly. "Oh, I'm just remembering," she explained. "The day in second grade when I discovered that not *everybody*'s dad does path integrals at the dinner table."

III. Henry's family

Henry is survived by his wife Beth Levine, their daughters Brett Abarbanel (married to Jared Okun) and Sara Abarbanel (married to Jonathan Feinberg), two grandchildren (Sara and Jonathan's children): Joanna and Isaac Feinberg, and Henry's three younger siblings: Alice Abarbanel (married to Alan Bern), Janice Abarbanel (married to Neil Porta), and Robert Abarbanel (married to Mary Beth Abarbanel).

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