Obituary
Krishna Shenoy (1968–2023)

Krishna Vaughn Shenoy was the most empathetic person we've ever known. He will surely be remembered for his scientific impact, but his remarkable kindness and devotion to others will also be a lasting part of his legacy. He could touch a person's life from a five-minute interaction, let alone a decade-long mentoring relationship. What we have learned from Krishna has made us better scientists and, more importantly, better people.

Krishna passed away on January 21, 2023, at age 54 after a long struggle with pancreatic cancer. He was first diagnosed in 2011, finally succumbing nearly 12 years after his diagnosis. We had begun to think he was invincible. Throughout his illness, Krishna continued to live his life with a sense of purpose and also with a sense of play and wonderment. He squeezed as much life, nurturing, and good work into his 54 years as a person possibly could.

Krishna's scientific legacy can be roughly divided into two categories: contributions to brain-computer interface (BCI) systems to help people with paralysis and contributions to our basic science understanding of how the brain controls movement. Our discussion of his scientific legacy here focuses on the former. Other tributes to Krishna will focus on the latter. There are more lessons to learn from Krishna's example, and stories to cherish, than can possibly fit into any short piece, but we hope to share with those who did not know him a sense of the magic and joy that he brought to science and mentoring.

Beginnings in BCI: Caltech (1996–2001)
Krishna's PhD in electrical engineering and computer science at MIT centered on optoelectronics, and his research earned the prestigious Hertz Foundation Thesis Prize. During his graduate years, he had developed a fascination with the brain, and he chose to pursue neuroscience thereafter. When Krishna arrived at Caltech as a postdoc in 1996, he was already determined to bring an engineer's

mindset to the practice of systems neuroscience.

Even from his first days in neuroscience, Krishna prioritized relationships. He made a point of getting to know each member of the lab, hearing what they were working on, and sharing his enthusiasm for what he hoped to do. He convened an after-hours journal club to assemble a team to discuss the early neural decoding papers that were just beginning to emerge. Krishna's first BCI paper[1] applied these concepts to the newly mapped parietal reach region. This work broke new conceptual ground: rather than relying solely on movement command signals from motor cortex, BCIs could now harness higher-level signals, such as motor planning, for BCI control.

BCI research in the laboratory: Stanford (2001–2012)
Krishna arrived at Stanford with a vision to create clinically viable BCI systems. Ever the engineer, he wanted to introduce rigorous performance metrics that could facilitate comparison across BCI systems. Krishna believed this would enable the field to advance in a unified fashion, with clear objectives and measurable progress.

Krishna's lab vision rested on engineers and neuroscientists working closely together and learning from each other. Everybody participated directly in the lab's experiments, no matter their prior background. This enabled each individual to deeply understand all facets of the

Krishna Shenoy (Image credit: Wikipedia)

research and engendered profound empathy among members of the team. It was also a manifestation of Krishna's faith in people that they could accomplish things beyond what they believed themselves to be capable of.

This vision and collaborative atmosphere yielded a new BCI for discrete key selection, akin to a computer keyboard.[2] Krishna's key insight was that during typing, the details of the movement are irrelevant—only the key that is selected matters. Inferring intended keys directly from brain activity could render a fast, accurate typing system. Krishna also proposed a single performance metric that could be used to compare different BCI systems: bits per second (bps). This research not only demonstrated unprecedented performance of a BCI system but also began implementing Krishna's vision of guiding the field by quantifying progress.

A second breakthrough came from thinking of BCIs as closed-loop control systems. This led to a new BCI that could provide fluid, graceful movements reminiscent of natural movements.[3] For the videos of the monkeys using the BCI, Krishna would emphasize how important it was to show segments that were representative and unedited. This reflected his unwavering commitment to the highest standards of being true to the data. He emphasized that only by fully reporting a system's performance, "warts and all," could the community assess whether BCI systems were actually ready for clinical use.

BCI research in the clinic: Stanford (2012–present)
To ensure the advances made in the laboratory would translate to clinical BCIs, Krishna partnered with Jaimie Henderson, a neurosurgeon at Stanford. Their partnership, which they sometimes described as a "professional marriage," started in 2005, when Jaimie and Krishna first began trying to monitor human brain activity using high-resolution electrodes—the same devices that Krishna's

lab used in monkeys—during deep brain stimulation surgeries. This led to a shared lab focused on clinical translation to help people with paralysis. Because Krishna's goal was always to pursue research that could benefit people, his instinct was to forge teams rather than compete, and so the pair joined the multisite BrainGate human clinical trial. In 2013, the Stanford team's first research participant achieved BCI control.

Early translational work sought to dispel stubborn beliefs in the field: that clinical intracortical BCIs were not capable of high performance and that any high performance achieved would fail a few months after implantation. In this pursuit, Krishna and Jaimie brought the same engineering rigor to the human lab as was present in the monkey lab. The team's work first focused on BCIs for "point-and-click" cursor control, like a computer keyboard and mouse—a natural extension of Krishna's prior work with monkeys. Ultimately, the team achieved typing rates of 6–8 words per minute (wpm) and bit rates surpassing 1.5–4 bps,[4] which was a 2- to 4-fold improvement over previous demonstrations in humans. Their study participants could achieve these metrics even years after implantation. From there, the lab went on to develop systems for communication through BCI-controlled handwriting (16–18 wpm and 6.56 bps).[5]

Most of Krishna and Jaimie's clinical BCI work was during Krishna's battle with cancer. In fact, Krishna co-authored even more papers during the 10 years after treatment began than he had during the 10 years prior to his diagnosis. Science seemed to buoy Krishna—many of us who met with him during those years noticed how his fatigue at the beginning of a conversation was surmounted by his vigor as the discussion deepened, as if the time with friends and colleagues, thinking together about science, was something he thrived on. His science and his purpose seemed to sustain and uplift him during those painful years, as did his family and longtime friends.

In recent years, Krishna also provided guidance to the companies that have begun to develop BCIs. Krishna's drive to bring BCIs to patients led him to bridge academia, industry, and clinical practice. Through his way of being in the world, Krishna transformed the fields in which he worked—BCI development and primate neurophysiology. He brought rigor, insight, and a sense of kindness and collaboration that we can see continuing to ripple and spread through these fields.

A pervading sense of joy

Krishna approached his life with the same joyful play that he brought to his science. And, in his personal life, just as in science, once he set his sights on an objective there was no stopping him. He was an inveterate prankster, often configuring his schemes so that they could not be traced back to him, with only the hint of a smile betraying his role. But always, his pranks were an invitation: to retaliate in a joyful escalation or to celebrate a person's individuality. We all have cherished stories of being called on to share an embarrassing experience with a room full of strangers, soon to be friends. Or of getting dragged into an early-morning food fight in some faraway city, ending in the need to change your shirt just before your first-ever conference presentation. Or of noticing during your presentation to the lab that everyone in your audience suddenly and inexplicably craved a banana at the exact same moment, as if compelled by some unseen impetus.

Magic mentoring

Krishna always put people and relationships first and let the science follow from there. Many of us, now running labs of our own, strive to capture the magic of his mentoring style. In guiding our trainees, we've often asked ourselves, and each other, "What would Krishna do?" Looking back, it was easy to take for granted his mentorship skills, and now we realize how difficult they can be to replicate. But it befalls us to try our best to capture his style, share it, and encourage others to strive with us to adopt it too.

As far as we can tell, Krishna's magic as a mentor flowed from three characteristics of his. First, Krishna began by listening. Whether it was your first conversation with him or your hundredth, it opened with Krishna expressing a genuine curiosity about you—your passions, your progress, your roadblocks, your work-life balance. He started by hearing where you were at, and then he came to meet you there. Second, Krishna knew us deeply. It was impossible to hide our weaknesses from Krishna, even if we thought we wanted to, and his ability to pinpoint our areas for improvement was uncanny. But these sometimes-blunt observations were always delivered with love and support, and we would invariably walk out of his office after a difficult private conversation feeling elevated and with a newly identified path to growth. He also saw our struggles and our burdens—sometimes even before we could name them ourselves—and he helped us carry them, making them lighter. Third, Krishna understood that each of us was on a personal journey. For so many of us, he helped us to identify our greatest aspirations, and he encouraged us to pursue them, supported us along the way, and reminded us of them when we sometimes lost sight. Many of us who had the privilege of having been mentored by Krishna feel that we have the careers we love thanks to him.

Insofar as we can divine Krishna's mentoring magic, it seems it was this: believe in people. Know them deeply. Be present for them. And always begin with kindness and compassion. We all believe that if we could mentor with as much heart and mind as Krishna did, then those who entrust themselves to our guidance would not only achieve their very best science but also live their fullest lives. He lives on in our hearts, reminding us of what we are capable of, leading us to be better people, and calling upon us to fulfill our potential, always with a sense of joy and play.

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REFERENCES

1. Shenoy, K.V., Meeker, D., Cao, S., Kureshi, S.A., Pesaran, B., Buneo, C.A., Batista, A.P., Mitra, P.P., Burdick, J.W., and Andersen, R.A. (2003). Neural prosthetic control signals from plan activity. Neuroreport *14*, 591–596.

2. Santhanam, G., Ryu, S.I., Yu, B.M., Afshar, A., and Shenoy, K.V. (2006). A high-performance brain-computer interface. Nature *442*, 195–198.

3. Gilja, V., Nuyujukian, P., Chestek, C.A., Cunningham, J.P., Yu, B.M., Fan, J.M., Churchland, M.M., Kaufman, M.T., Kao, J.C., Ryu, S.I., and Shenoy, K.V. (2012). A high-performance neural prosthesis enabled by control algorithm design. Nat. Neurosci. *15*, 1752–1757.

4. Pandarinath, C., Nuyujukian, P., Blabe, C.H., Sorice, B.L., Saab, J., Willett, F.R., Hochberg, L.R., Shenoy, K.V., and Henderson, J.M. (2017). High performance communication by people with paralysis using an intracortical brain-computer interface. Elife *6*, e18554.

5. Willett, F.R., Avansino, D.T., Hochberg, L.R., Henderson, J.M., and Shenoy, K.V. (2021). High-performance brain-to-text communication via handwriting. Nature *593*, 249–254.