Karthik Shankar, 1979-2023

Marc W. Howard

Dr. Karthik Hari Shankar passed away suddenly from natural causes on September 5, 2023. He was 44 years old. Karthik was trained as a theoretical physicist and subsequently worked in diverse fields, including gravity, mathematical psychology, and theoretical neuroscience. His contributions to theoretical neuroscience were towering. He was solely responsible for the idea that memory for the past in the brain is encoded via real Laplace transform—an idea that has been incredibly productive in understanding neuroscience and cognitive psychology. Simultaneous with his work in theoretical neuroscience, he formulated an alternative theory of gravity. This theory produces the same kinematics as general relativity in 4-D space-time while solving conceptual problems inherent in general relativity and making very different with general relativity and making very different predictions about cosmology.

Karthik graduated with a PhD in black hole physics from the University of Florida in 2007. After graduation, he moved to Syracuse, NY with his life partner Dr. Aparna Baskaran who was at the time a post-doc in the Syracuse University Department of Physics. Karthik had decided he wanted to study cognition as a physics problem. Karthik had many conversations with leading cognitive and computational neuroscientists throughout the east coast of the US. During one of these visits, he had a chance meeting with Per Sederberg, at the time a post-doc at Princeton, who suggested my name to Karthik. As it turns out, Karthik's home in Syracuse at the time was walking distance from my lab. After discussions over several months, Karthik Shankar joined my lab at Syracuse University as a postdoctoral fellow.

Karthik insisted that we install a small chalkboard in his new office, and we began work. Over the next year or so, Karthik mastered the temporal context model (TCM), a distributed memory model designed to account for findings from laboratory memory experiments where participants learn and recall lists of words. We worked closely with Udaya Jagadisan, then a Master's student at Syracuse, developing the "predictive temporal context model" (pTCM Shankar, Jagadisan, & Howard, 2009; Howard, Shankar, & Jagadisan, 2011). The basic idea of pTCM was to treat a corpus of natural text as if it was a long list of words and use mechanisms for list learning to discover semantic embeddings for the words in the language.

Shortly after publishing the pTCM papers it became clear that temporal context models, whatever their merits, were certainly wrong in important ways. We needed a new mathematical formulation for temporal context. I had ideas about the properties that this new form of temporal context would need to have to solve the problems we were facing in cognitive psychology and semantic memory. Karthik had the singularly brilliant idea to use a real Laplace transform as an intermediate step to construct this scale-invariant temporal context. Over the next few months, he worked out (with minimal contributions from his advisor) a neural network model to construct and invert the Laplace transform, yielding a scale-invariant neural representation of the past (Shankar & Howard, 2010, 2012, 2013). The Laplace domain variable s is used to contruct a continuous neural space that forms a temporal memory for the recent past. The equations describe a neural timeline that corresponds to our phenomenological experience of past time as a continuous variable.

I remember a particular moment where it became clear that Karthik's work would be of lasting value. We (again, mostly Karthik) had worked out on the chalkboard how neurons in the neural network would fire as a function of time after the presentation of a stimulus. I remember thinking that this was a really elegant idea but it seemed too elaborate to expect from a real neural circuit. The next week we were at a conference in Boston where Howard Eichenbaum was presenting unpublished neurophysiological data from his lab. He showed neurons in the rodent hippocampus behaving just like the equations that were on the board back in Syracuse. Since then, many papers from labs at Boston University and around the world have confirmed predictions of Karthik's early work in what are now called "time cells" (MacDonald, Lepage, Eden, & Eichenbaum, 2011). Moreover, we also now know that the mammalian brain computes the Laplace transform of time including in regions that project directly to the hippocampus (Tsao et al., 2018; Bright et al., 2020). The fact that the equations Karthik worked out from completely abstract considerations aligned so well with the firing of neurons in the mammalian brain speaks to the deep level of physical insight he brought to bear on the problem.

Karthik pursued the implications of this neural network for cognitive psychology and neurophysiology in a series of papers written with colleagues at Syracuse and at Boston University starting in 2011. These papers include sophisticated treatments of cognitive models (Shankar & Howard, 2012; Howard, Shankar, Aue, & Criss, 2015) as well as detailed neurophysiology (Howard et al., 2014; Shankar, Singh, & Howard, 2016), pointing to the interdisciplinary implications of Karthik's foundational work. It is fair to say that Karthik's work in theoretical cognitive neuroscience was years, if not decades, ahead of its time. His work immediately had a profound effect on my understanding of the mind and brain, and has shaped essentially every aspect of the work I have done with my students and collaborators over the roughly 14 years he developed this hypothesis. In recent years, as the empirical story has come into focus, these ideas have also gradually started to become accepted by the wider community of researchers in cognitive science and neuroscience. It is not an exageration to say that Karthik's contributions changed the trajectory of our study of the mind and brain and may yet prove critical to development of a satistfactory theory of cognition.

Throughout the time he was laying the groundwork for a physics of the mind, Karthik also worked steadily in more traditional physics, developing an alternative theory of gravity, initially with Kameshar Wali, Distinguished Research Professor Emeritus at Syracuse University (Shankar & Wali, 2010; Shankar, Balaraman, & Wali, 2012). This theory assumes a five dimensional (rather than four dimensional) space-time, with torsion hiding the extra dimension (THED). THED produces the same kinematics as Einstein's equations in 4-D. However, although THED accounts for black holes, unlike standard general relativity, the equations of THED do not admit "naked singularities". Karthik felt strongly that singularities are a deeply inelegant property of general relativity and that this property of THED was an important advantage for this theory.

The theories can also be distinguished empirically. THED makes very different predictions than general relativity at the cosmological level. The cosmological equations of THED do not require a big bang but admit oscillatory solutions (Shankar et al., 2012; Shankar, 2017). The cosmological equations of THED change the estimates of the magnitude of dark energy and dark matter necessary to account for astronomical observations about the large-scale structure of the universe. Using supernovae redshift data to constrain the theory, Karthik found that adopting the cosmological equations from THED effectively eliminates the need for dark matter and dramatically reduces the need to postulate dark energy (Shankar, 2020), effectively eliminating one of the most persistent problems in contemporary cosmology.

THED could lead to more dramatic theoretical and empirical implications. Karthik proposed in an offhand remark in the 2020 paper that particles in 4D could occupy every position in the fifth dimension effectively forming a string. I distinctly remember conversations where he expressed the opinion that it should be possible to follow the connection between THED and string theory to construct an elegant theory of quantum gravity. In summer of 2023, shortly before his untimely passing, he was working out *stunning* empirical implications of THED. General relativity predicts that the path taken by light will be bent toward a massive object. The solar eclipse experiments of 1919 confirmed this prediction providing dramatic evidence for general relativity. Karthik became convinced that THED makes an extremely counterintuitive prediction. Depending on the precise distribution of mass, THED predicts that massive objects can either attract *or repel* light. This hypothesized "concave gravitational lensing" phenomenon, as Karthik referred to it, could in principle be observed by observing pairs of stars as massive objects pass in front. It is difficult to express the impact that this observation would have on our understanding of the physical world.

Karthik Shankar had far-reaching scientific interests that extended beyond neuroscience and gravity. In response to the dissatisfaction around the 2020 elections he turned his attention to ways to improve democracy. Karthik's insight was that in a zero-sum system candidates are incentivized not only to convince voters of their positive attributes but also to convince voters of their opponents' negative attributes. This dynamic contributes to political polarization. Karthik worked out a system, normed negative voting (Shankar, 2022), that gives a more nuanced expression of voter's wishes. Voters can distribute both positive and negative votes to a slate of candidates. The system results in a two-dimensional rating for candidates allowing organizations to select leaders according to a variety of heuristics. For instance, a candidate who is the first choice of a bare majority of voters but receives a large number of negative votes could lose to a candidate who is acceptable to a broad range of voters. Organizations could thus incentivize candidates to build consensus and disincentivize political polarization.

Looking back on his scientific career, it is remarkable that Karthik was able to contribute at such a high level to such different fields. Karthik often said, "A true theorist should be able to approach any problem and find its essence." Karthik Shankar was a true theorist.

References

Bright, I. M., Meister, M. L. R., Cruzado, N. A., Tiganj, Z., Buffalo, E. A., & Howard, M. W. (2020). A temporal record of the past with a spectrum of time constants in the monkey entorhinal cortex. *Proceedings of the National Academy of Sciences*, *117*, 20274-20283.

Howard, M. W., MacDonald, C. J., Tiganj, Z., Shankar, K. H., Du, Q., Hasselmo, M. E., & Eichenbaum, H. (2014). A unified mathematical framework for coding time, space, and sequences in the hippocampal region. *Journal of Neuroscience*, *34*(13), 4692-707. doi: 10.1523/JNEUROSCI.5808-12.2014

Howard, M. W., Shankar, K. H., Aue, W., & Criss, A. H. (2015). A distributed representation of internal time. *Psychological Review*, *122*(1), 24-53.

Howard, M. W., Shankar, K. H., & Jagadisan, U. K. K. (2011). Constructing semantic representations from a gradually-changing representation of temporal context. *Topics in Cognitive Science*, *3*(1), 48-73.

MacDonald, C. J., Lepage, K. Q., Eden, U. T., & Eichenbaum, H. (2011). Hippocampal "time cells" bridge the gap in memory for discontiguous events. *Neuron*, *71*(4), 737-749.

Shankar, K. H. (2017). Horizonless, singularity-free, compact shells satisfying NEC. *General Relativity and Gravitation*, *49*(33).

Shankar, K. H. (2020). Eternally oscillating zero energy universe. *General Relativity and Gravitation*, *52*(23).

Shankar, K. H. (2022). Normed negative voting to depolarize politics. *Group Decision and Negotiation*, *31*, 1097-1120.

Shankar, K. H., Balaraman, A., & Wali, K. C. (2012). Metric theory of gravity with torsion in an extra dimension. *Physical Review D*, *86*(2), 024007.

Shankar, K. H., & Howard, M. W. (2010). Timing using temporal context. *Brain Research*, *1365*, 3-17.

Shankar, K. H., & Howard, M. W. (2012). A scale-invariant internal representation of time. *Neural Computation*, *24*(1), 134-193.

Shankar, K. H., & Howard, M. W. (2013). Optimally fuzzy temporal memory. *Journal of Machine Learning Research*, *14*, 3753-3780.

Shankar, K. H., Jagadisan, U. K. K., & Howard, M. W. (2009). Sequential learning using temporal context. *Journal of Mathematical Psychology*, *53*, 474-485.

Shankar, K. H., Singh, I., & Howard, M. W. (2016). Neural mechanism to simulate a scale-invariant future. *Neural Computation*, *28*, 2594–2627.

Shankar, K. H., & Wali, K. C. (2010). Kaluza–klein theory with torsion confined to the extra dimension. *Modern Physics Letters A*, *25*(25), 2121–2130.

Tsao, A., Sugar, J., Lu, L., Wang, C., Knierim, J. J., Moser, M.-B., & Moser, E. I. (2018). Integrating time from experience in the lateral entorhinal cortex. *Nature*, *561*, 57-62.