

# A Circle of Life

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I am honored and humbled to receive the Timoshenko Medal, joining the illustrious list of past recipients, including many of my heroes, mentors, and colleagues. I thank the ASME and the Applied Mechanics Division for selecting me to receive the award. I also thank the nominator and those who supported the nomination. The honor belongs to all my students, postdoctoral scholars, visitors, and collaborators and is a recognition of their collective contributions to my research at Caltech over the last 30+ years.

I have admired Stephen Prokopovich Timoshenko for his lucid presentation, simple and elegant approach to solving problems, and interest in the history of mechanics. I first learned the basic concepts of solid mechanics, such as bending and torsion, from his textbook with D. H. Young on Elements of Strength of Materials. I have benefitted from three of his books on elasticity, structures, and stability in my teaching.

The conferral of the award allows me to share with you my journey in mechanics. I am an accidental academic and researcher. I grew up on a farm in the Coimbatore district of Tamil Nadu, India. Neither of my parents had completed high school, but they supported my education and encouraged my curiosity. I received my primary and secondary school education in my village. The school had a modern outlook and inspiring teachers but needed proper textbooks. Sometimes, ignorance is bliss. I found much joy in proving theorems in geometry, which Euclid had discovered more than two millennia earlier. An important turning point came when I went for my pre-university studies at St. Joseph's College in Trichy. Here, I had my first exposure to experimental labs and a library, where I discovered Feynman's Lectures on Physics.

After completing my one-year pre-university class, I pursued my bachelor's degree in mechanical engineering at the Regional Engineering College, Trichy. The curriculum, besides theory, emphasized practical skills such as drafting, machining, and laboratory work. For my senior group project, I worked on the simulation of flow around the impellers of a pump under the guidance of Professor K. P. Mohammed, which gave me my first introduction to research and computational fluid dynamics.

I came to the U.S. in the fall of 1981 to pursue my graduate studies in solid mechanics and structures at Brown University. I attended classes offered by gifted teachers and masters in their fields, including Rod Clifton, Ben Freund, Joe Gurland, Rick James, Michael Ortiz, Jack Pipkin, Fong Shih, Subra Suresh, and Jerry Wiener. As I searched for an advisor, I was attracted to Rod Clifton's laboratory, where I thought I could use the practical skills I had learned in college. For my thesis on dynamic fracture, I developed a plate impact technique by subjecting a planar crack in a disk to stress wave loading of a microsecond duration. Ben Freund had analyzed this problem in a series of elegant papers published in the Journal of the Mechanics and Physics of Solids in the early 70s. These served as a guide for designing and interpreting my experiments. I was trained initially in the intricacies of plate impact

experiments by Amos Gilat and Gaddi Meier and was subsequently supported by my fellow lab mates Rich Klopp and K. T. Ramesh. I also benefitted from my interactions with Toshio Nakamura, Brian Moran, and Yves Leroy, who helped me with the numerical simulation of my experiments.

Rod Clifton was an outstanding thesis advisor and mentor who let his students explore and figure things out independently. He was readily available for discussions, and his keen analytical mind provided deep insights into complex problems, even purely experimental ones. He placed particular emphasis on experiments that are interpretable within the mechanics framework. He was also an early pioneer in interdisciplinary research with materials science and biomechanics. Merc and Rod Clifton cared deeply about students' well-being and made them feel at home, including at their family's Thanksgiving dinners.

Upon completing my Ph.D. thesis in 1986, I took up a postdoctoral position with Wolfgang Knauss at Caltech. The year I spent as a postdoc was a life changer and one of my professional life's best years. Knauss was a wonderful mentor who allowed me to explore and encouraged me to think about physical insights and applications in addition to mechanics. A few months into my postdoctoral work, I was persuaded by Ares Rosakis to apply for an open faculty position at the University of California, San Diego (UCSD). I joined UCSD in the fall of 1987, where I learned the ropes of teaching, mentoring, proposal writing, and all the other things associated with being a faculty member. Early in my career, I benefitted from interacting with excellent colleagues, including Sia Nemat-Nasser, Xanthippi Markenscoff, and Marc Meyers.

In 1990, I received an offer from Caltech to join its Aeronautics faculty, and I returned there in the spring of that year. The Graduate Aerospace Laboratories, known as GALCIT, is the home of the Aerospace department at Caltech and is a paradise for experimentalists. It was founded in 1928 by Theodore von Karman as an interdisciplinary research center focused on applied mechanics with application to contemporary problems. Weinong Chen became my first graduate student and designed the Kolsky (split Hopkinson) pressure bar for my lab, which is still operational. Soon after, Mark Walter joined, followed by Ghatu Subhash, who became the first postdoctoral scholar in my group. Together, we started exploring the behavior of ceramics under confinement and at high strain rates. In later years, we developed the shear-compression specimen (SCS) due to the efforts of Sang-wook Lee and Dany Rittel. This specimen helped us seamlessly explore the dynamic constitutive behavior of metals in the strain rate range of  $10^{-3}$  to about  $10^5/s$ . In later years, Murat Vural and Laurence Bodelot extended the applications of the SCS to investigate other high-strain rate phenomena in metals.

Though my background was in plate impact experimental techniques, I concentrated initially on building my lab around a relatively more straightforward technique of the Kolsky (split Hopkinson) bar. Shortly after I joined Caltech, I was persuaded by a senior colleague in materials science, Thad Vreeland, to take over his powder gun plate impact facility. This paved the way for me to explore problems in shock physics from a mechanics perspective. With Wei Tong and Karina Montilla, we investigated the shock consolidation of materials. Shock wave experiments on layered and particulate composites by Shiming Zhuang and Mike Rauls and modeling by Alain Molinari provided insights into the role of dispersion and dissipation on shock structure in heterogeneous materials. Justin Brown's work exploited the idea of Mach stem to enhance the pressure for a given impact velocity. In collaboration with Michael Ortiz, Addis Kidane used impact problems for uncertainty quantification. More recently, Jack Weeks demonstrated the validity of using the one-dimensional shock wave analysis to describe the behavior of additively manufactured metallic lattices.

The powder gun also helped us open a new avenue of research based on the pressure shear plate impact experiments originally invented by Rod Clifton at Brown University. This technique enabled one to infer the state of stress and strain in a thin sample sandwiched between plates using the free surface measurements of normal and transverse particle velocities. The pressures one could achieve in this technique were limited by the Hugoniot elastic limit of the material of the anvil plates, typically less than 10 GPa. Our effort to extend the pressure range of the PSPI technique proved an exciting adventure because of the modifications needed to be made to the powder gun and dealing with the inelastic deformation of the anvil plates at high pressures. Christian Kettenbeil and Zev Lovinger were persistent and overcame many obstacles in this effort with crucial help from Mike Mello. This enabled Suraj Ravindran and Vatsa Gandhi to apply the high-pressure PSPI technique to characterize the strength and plasticity of metals at pressures of up to 40 GPa.

Caltech's small size and lack of departmental and disciplinary boundaries are conducive to collaboration among colleagues and disciplines. I have been fortunate to have collaborated with several outstanding colleagues who have contributed to my growth and helped broaden my horizons. The collaborations allowed me to participate in the development of new experimental techniques and instrumentation. In this context, I was guided by the words of Galileo Galilei, "Measure what is measurable, and make measurable what is not so."

In my first collaborative project with Ares Rosakis, whom I have known for over 40 years as a colleague, friend, and mentor, we measured the Taylor-Quinney factor, the fraction of plastic work converted to heat. It was generally assumed to be a constant with a value of 0.9. We combined our complementary expertise and facilities of the Kolsky bar and an infrared detector for *in-situ* dynamic temperature measurement. Through the works of Jim Mason and Jon Hodowany, we showed that the fraction of plastic work converted to heat was not a constant but a function of strain and strain rate. We also benefitted from collaborating with Phoebus Rosakis, who used continuum thermodynamics to model the stored energy of cold work. This further led to several other stimulating and enjoyable collaborations with Ares on thermomechanics, including investigating adiabatic shear bands and failure mode transition with Min Zhou, designing and building a high-speed thermal camera capable of taking 1 million frames/s with Alan Zehnder, and exploring dynamic fracture with Pradeep Guduru.

I have had a long-standing collaboration with Kaushik Bhattacharya, who introduced me to the field of active materials. Our initial focus centered around large strain actuation of ferroelectrics, which was thought to be limited to around 0.2%. Guided by Kaushik's insights on domain switching and energy landscapes, Eric Buresu built a simple apparatus that combined mechanical and electrical loading, whereby one could achieve about 1% cyclic actuation. This work was followed by other collaborations, including characterizing thin films by Rongjing Zhang, the motion of domain walls by Doron Shilo, and anisotropic fracture by Charlotte Kramer.

Though I was familiar with digital image correlation (DIC), I did not use it in my research until the early 2000s. Sam Daly applied DIC to study the inhomogeneous deformation in shape memory alloys, another area of Kaushik Bhattacharya's expertise. We also collaborated with him on the mechanics of heterogeneous peeling and adhesion through the work of Shuman Xia and Laurent Ponson. Louisa Avellar helped extend this work to investigate the fracture of 3D printed materials. In collaboration with Kathy Faber and Neal Brodrik, we showed that fracture energy can be enhanced through engineering defects in brittle materials.

I also had the pleasure of collaborating with Jose Andrade on mesoscale granular mechanics in characterizing inter-particle forces and force chains in opaque granular materials using digital image correlation and with Bill Johnson on the thermomechanical behavior of metallic glasses and their composites through the works of Jun Lu and Min Tao.

My journey in biological materials started through a conversation with Dave Tirrell while we were both part of the NSF MRSEC Center at Caltech. He was interested in understanding cell-matrix interactions as part of his broader research on developing artificial proteins. This led to the development of 3D traction force microscopy for measuring cellular forces through the work of Christian Franck, along with Soon-sung Hong and Stacey Maskarenic. It was further extended to study biological processes such as cell division through the work of Jacob Notbohm and Ayelet Lesman. Our decade-long collaboration with Dave Tirrell's group enabled the development of a new quantitative imaging technique for measuring cell-generated forces in 3D using confocal microscopy and digital volume correlation.

Mechanics is a field rich with many open problems, challenges, and opportunities, especially at the intersection with other fields, including biology, chemistry, geology, and materials. It is an exciting time to be part of the applied mechanics community. We can bring our fundamental concepts in mechanics, namely the conservation of mass, momentum, and energy, to address many of the contemporary problems. Taking advantage of the rapid technological advances in several areas, including computing, data-driven techniques, machine learning, imaging, and instrumentation, mechanics will continue to play a significant role in addressing problems of importance to society, including energy, environment, health, mobility, security, and sustainability.

As an experimentalist, I am excited by the opportunities created by emerging technologies. It is worth recalling a quote by the Nobel laureate Steven Chu, "Invent a new instrument, invent a new technique, the world opens up." The possibilities and research problems are infinite, limited only by our imagination. As we explore new areas, let us not forget our basics in mechanics, from atomistic to continuum, which is our strength. It is important to continue to educate and train our students on the rigors of both classical and contemporary mechanics of solids and structures, enabling them to advance their knowledge and find solutions to problems of the future.

Research is an intensely personal experience and often a lonely journey. In this journey, we need the support and encouragement of the community, whether it be our colleagues or the broader mechanics community. We also need mentors, regardless of the stage of our career. I have been fortunate to have had many wonderful mentors at Brown University, Caltech, and elsewhere. In my journey, I have often been guided by three things that I often tell my students: when you have an idea, first, 'just do it,' which is Nike's slogan; second, 'go for it,' and, lastly, when you come to a fork, take it, which is a phrase attributed to Yogi Berra.

Though we are connected more than ever through technology, there are no substitutes for personal interactions at conferences and workshops. I highly encourage taking sabbaticals, which gives time to reflect, help assess oneself and one's institution from a distance, appreciate what life has given us, recharge, and generate new ideas. I am grateful for my sabbaticals at Ecole Polytechnique, the Tokyo Institute of Technology, and the Indian Institute of Science.

I started my academic journey in India and my research in dynamic fracture and stress waves in the United States. Both in life and research, I have come full circle. I have returned to India to help build a new research University, and my recent research is concerned with applying shock waves to study the behavior of materials at high pressures. Reflecting on my life's journey, "...I consider myself the luckiest man on the face of this earth," a phrase I have borrowed from Lou Gehrig's farewell speech in 1939.

My research and career would not have been possible without the support of my family. I thank my wife, Sandhya, for her constant love and support over the last 35 years. She has been my rock, and she kept our family together through my various adventures. She has also inspired me and kept me grounded during challenging times. Our children, Ajay and Vaishali, have been wonderful and made my life enjoyable outside academia. I think they have forgiven me for reading journal papers instead of watching them play soccer in their younger days.

I am grateful to the United States for welcoming me, initially as a student and later as an immigrant, and for giving me many excellent opportunities that have made everything possible.

In conclusion, I thank my teachers, mentors, colleagues, students, postdoctoral scholars, collaborators, GALCIT, Caltech, Jio Institute, friends, and family for all they have given me. I wouldn't be here today without their unwavering faith, encouragement, and support.