



# In memoriam of Robert P. Behringer

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Robert (Bob) Behringer was an extremely talented scientist, conscientious and kind mentor, and creative and trusted collaborator. He earned his Ph.D. in Physics from Duke University in 1975, working with Horst Meyer on exquisite experiments to understand critical phenomena in liquid helium. After making numerous discoveries concerning Rayleigh-Benard convection in low-temperature fluids, Bob made the bold move to the new field of “granular physics” in the mid-1980s. Bob, along with Sidney Nagel and Heinrich Jaeger, from the University of Chicago helped to develop the field in the 1980s and 1990s. Bob was particularly well-known for his careful measurements of the interparticle forces in two-dimensional granular systems using photoelasticity, which gave key insights into the structure of force chains and the phenomenon of shear-induced jamming. Bob was named the James B. Duke Professor of Physics in 1994, elected fellow of the American Physical Society in 1993, and a Fellow of the American Association for the Advancement of Science in 1998.

Bob was a champion of the granular materials community, serving as an Editor-in-Chief of *Granular Matter*, serving on the board of Powders & Grains, advocating for granular materials through his leadership positions in the Topical Group on Statistical and Nonlinear Physics of the American Physical Society, and hosting numerous national and international scientific meetings. This collection of *Granular Matter* is dedicated to Bob; it includes 47 peer-reviewed articles from Bob's students, postdoctoral researchers, colleagues, and collaborators that span the full range of granular materials research, as well as related work on soft and hard particle suspensions. Below, we also include 30 personal tributes, which discuss the impact that Bob had on the

lives and careers of the scientists with whom he interacted (Figs. 1 and 2).

## Tributes

**Aghil Abed Zadeh, Cacey Stevens Bester, David Chen, Payman Jalali, Ryan Kozlowski, Lihui Li, Dong Wang, Meimei Wang, Yue Zhang, Yiqiu Zhao, Yuchen Zhao, Hu Zheng, Duke University**

The most recent members of LTB (Low-Temperature Behringer lab) would like to thank Bob for his mentorship and guidance both in and out of the lab. For those of us who have recently graduated, we remember fondly our daily interactions with a first-class scientist who could draw connections among a wide array of physical and mathematical concepts. Whether it was preparing manuscripts, conference talks, or formal exam presentations, Bob challenged and encouraged us, teaching us how to develop and execute a research plan and how to share that work with scientists and society at-large. For us younger students who will continue our granular research with other mentors, we are grateful for the start we had with Bob and will always remember his intelligence, vision, productivity, and endearing sense of humor. From day one, he expressed an enthusiasm for physics research and outreach that was and remains contagious. Lastly, for all of us, we move forward knowing that we were very fortunate to learn under a thoughtful scholar, skilled experimentalist, and compassionate mentor (of about 30 Ph.D. students, over 20 post-docs, and several high-school students) who fundamentally changed the way we look at grains-in more ways than one!

## Bulbul Chakraborty, Brandeis University

My first memory of Bob is of him sitting at the back of a room at an American Physical Society March meeting session chewing on his pencil! He had just heard a talk by my then student, Silke Henkes, and was busy scribbling away in

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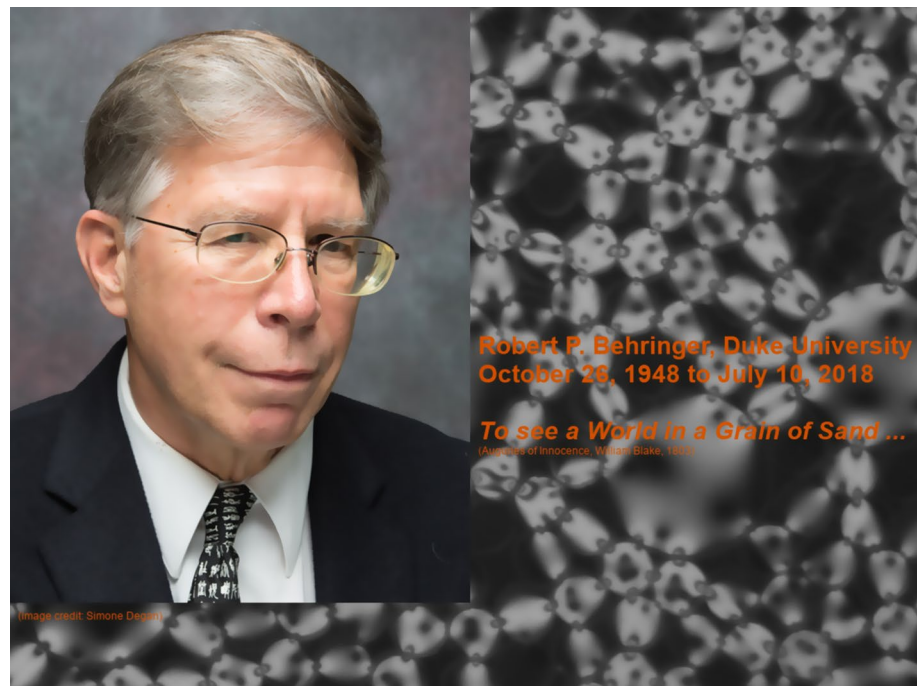
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**Fig. 1** Portrait of Prof. Robert Behringer and image of force chains in packings of photoelastic disks. Portrait courtesy of Simone Degan



his notebook. It turned out that he was working out how to use the theory that Silke had presented to analyze some old experiments of his. That was the beginning of our decade long friendship and collaboration. I don't think it would be an exaggeration to say that my work would not have proceeded in the direction that it has if it was not for Bob. More importantly, he was always there for me, and I tried to be there for him. The three months that we spent together at KITP in the spring of 2018 will be a source of inspiration for me always. There are so many moments when I wish he was there for me to pick up the phone and talk to him when I feel lost in formalism and need his help to translate my abstractions to reality.

#### **Abram Clark, Naval Postgraduate School**

I chose to work with Bob as my Ph.D. advisor partly because I thought the problems he studied were interesting, but also because he was just a really kind person. In fact, I think I had subconsciously assumed that he wasn't that successful because he was so understated and humble. In November of 2009, I went to my first conference (Division of Fluid Dynamics in Minneapolis). There, I realized that, not only was Bob more successful than I thought, he might be the most important guy in our field. It was impossible to talk to him, since there was a crowd of people that followed him wherever he went, and every presentation I saw included pictures of his photoelastic experiments. When you were in Bob's group, you were part of his family, including dinner parties with Sue

and the annual day at his lake house. Bob has made me (and many others) a better scientist and a better person. I will miss him greatly.

#### **Karin Dahmen, University of Illinois, Urbana-Champaign**

We greatly miss Bob—who is not only a great scientist, but also a wonderful teacher, mentor and friend with a huge heart for people. He made many groundbreaking contributions to science. He was always quick to listen, and highly supportive to everyone around him. He always found time for a good discussion, a kind and encouraging word or wise advice when needed. He is a great example to all of us and he is sorely missed.

#### **Morton Denn, The City College of New York**

Bob and I came from very different disciplinary backgrounds, and, while I had long appreciated his excellent research, we had one-on-one technical conversations only in recent years, when we began to attend the same meetings. We had a particularly good talk at KITP in January 2018, where we exchanged ideas about the development of forces in concentrated suspensions, and I was looking forward to continuing that interaction. He has had a profound impact on what we do.

**Fig. 2** This photo captures the essence of Bob. He can engage you in deep and productive scientific discourse but somehow this is always laced with laughter and play. The photo has been reproduced with the permission of Prof Behringer's family.



### Joshua Dijkstra, Wageningen University

Bob for me was magical. There was magic in how he sometimes came up with intractably clever solutions to experimental problems. There was magic in how he could turn what seemed like a mundane result into a good paper. There was magic in how with his humble demeanor he stimulated so much progress in the granular community. Was he mercurial? Well I think there was just a lot of mercury in the labs. Bob was the cohesive potential for keeping much of the granular community together. His science was shear-jammed solid. A warm person, definitely not low temperature. I see Bob as photoelastic: by squeezing him, all you got was a colorful response, showing you what your strengths are. Bob was about puns too, yet even coming up with worse ones than his will not make him come back. I miss him.

### Hisao Hayakawa, Kyoto University

I had many occasions to discuss shear jamming of frictional grains with Bob and I learned a lot from him. I could not imagine that the discussion with him at the last American Physical Society March Meeting in 2018 would be the last occasion. I express my deepest sadness about his death.

### Meiyang Hou, Institute of Physics, Chinese Academy of Sciences

As one of the leading figures in granular matter physics, Bob's sudden passing is a big loss to his colleagues in China. We lost a colleague, a friend, and a mentor forever. I have known Bob since our first international conference in 2001

on Pattern Formation and Self-Organization in Nonlinear Complex Systems in Beijing, when I first entered the field of granular physics. After that, Bob and I met at numerous conferences, such as Powders and Grains, Gordon Research Conferences, and several conferences in China, such as the Shanghai conference on packing problems (2016) and Guiyang conference on granular flow in 2017. At the meeting in Guiyang, Bob made helpful suggestions on annular shearing in microgravity experiments. We were looking forward to the collaboration, but he left us forever. We will now continue the experiments with fond thoughts and gratitude.

### George Hentschel, Emory University

Bob Behringer was one of the giants of the field of granular physics. His pioneering contributions to the measurement of the contact forces between grains by studying the forces in granular packings using two-dimensional photoelastic discs led directly to the identification and properties of stress lines revolutionizing granular physics in the last decade of the twentieth century. I mention this specifically as I have a long-standing collaboration with Professor Itamar Procaccia at the Weizmann Institute, and every time I enter his office I see a large image displayed of such stress fields, which really helps me appreciate their complexity in granular materials.

Though I had known of Bob Behringer's work for many years, it was only in July 2005 that I first met him at the XXV European Dynamics Days hosted by the Technical University of Berlin, Germany. He was an invited speaker and gave a talk entitled "*Fluctuations, correlations and transitions in granular materials*". By chance on a free afternoon we both decided to take a boat trip on the Spree at the same

time, where we discussed developments in granular physics and the history of Berlin since 1945 together, an afternoon I treasure.

### **Hans Herrmann, ETH**

Bob was a great friend and a great scientist. He pioneered controlled lab experiments of granular media and was one of the initiators of granular research within physics. He was a great teacher and formed within his very active group many renowned scientists. We became collaborators and close friends during his sabbatical in Paris. I very much enjoyed his gentle manners and admired his knowledge. After that time, we met many more times also with our families and founded together the journal *Granular Matter*. His unexpected departure was a big shock and a huge loss for me and for our community.

### **Heinrich Jaeger, The University of Chicago**

Granular matter research as a field owes so much to Bob. Bob was a bridge builder. In a body of work that has become a pillar of our field, he brought together ideas from physics, engineering, and applied mathematics and applied them in new ways. And with his warm, down-to-earth personality, he was instrumental in building new bridges that connected these different scientific communities. I dearly miss Bob's presence in this endeavor, and I miss him as a friend.

### **Jim Jenkins, Cornell University**

Bob Behringer influenced the field of granular physics in three significant ways. Perhaps most important was his belief that the methods of statistical physics were the key to understanding the behavior of the disequibrated, random systems of his interest; second was his educating, mentoring, and sharing his scientific vision and methods with a cadre of students and colleagues, who themselves became important contributors to the field; and third was his service to the field through his organization of and participation in numerous meetings, and his significant editorial responsibilities. He carried out all of these activities with warmth, good humor, and grace. It is impossible to imagine how the void left by his absence can be filled.

### **Ken Kamrin, MIT**

I remember meeting Bob in my second year of graduate school. The first thing I noticed was he was such a nice guy! And needless to say, a great scientist. Since then, as I grew up more academically, Bob was always there as a strong and supportive senior colleague to me. He and I have very different training and our approaches to granular media

employ different tools. But that never mattered to Bob. He was always encouraging and always working to get people together, to learn from each other and push forward. It is this exemplar of open-ness and warmth to new ideas and new people that I take with me most of all. We'll miss you Bob.

### **Lou Kondic, NJIT**

I do not know any other scientist achieving so much while remaining modest, approachable, and understanding. It was a pleasure knowing and working with Bob. For many of us, Bob will always remain an example of a great scientist who hasn't forgotten to remain a great person as well.

### **Mario Liu, University of Tübingen**

It was in the heydays of helium physics when I, playing with some theories, first met Bob, the conscientious and meticulous experimenter, whose results are wise not to doubt, around which you simply wrap your model. But grains were his real calling. Many decades later, I am again busy fitting my pet theory to his data, and that of his group—such as shear jamming. Some things just never change.

### **Stefan Luding, University of Twente**

Bob was not only an inspiring researcher and colleague for me, he influenced my research on granular matter so much! Also he became a good friend over the 25 years I knew him. I will always remember the great research visits to Duke, but also the time we spent together on many international conferences, like in Cargese or at several Powders & Grains events. His passing away was a shock and leaves a big gap for me.

### **Jeffrey Morris, The City College of New York**

Bob and I became acquainted about 15 years ago, but I really came to know him over discussions in the last five years about North Carolina history (NC being my home state) and through mutual efforts to find connections in the physics of dense suspensions and granular media. At the time of his passing, we were regularly emailing and calling one another about sessions we were jointly organizing on this topic at the 2019 American Physical Society March Meeting, and for me it was like our conversations were cut off mid-breath.

### **Sidney Nagel, The University of Chicago**

Bob Behringer started out his career by doing experiments on critical phenomena in liquid helium; he then jumped into experiments on granular media. It is hard to think of a more dramatic and drastic switch in experimental technique and

in scientific direction. It required an exquisite nose for interesting problems and great courage to move away from the highly technical area of cryogenic research into the comparatively less technical (but arguably more intellectually challenging) area of granular physics. What an amazing change! And what amazing courage!

Bob went on to carve out a distinct scholarly area in what is now a vibrant part of soft-matter science. Many followed his footsteps. We all know his scientific achievements. His papers will be remembered and cited for a long time to come.

But what I want to stress here, and hope is *never* forgotten, is his role as a leader in this field. What made Bob special to me was not just his science. Equally important was the way he helped make the field of granular materials a welcoming, open and fun community of researchers. It was a brand-new playground for physicists and from the very first, Bob welcomed others to work in the area he created. This included not only his students and postdocs, of which there are many who continue to lead and carry on his scientific tradition, but also his numerous colleagues at other institutions. I was fortunate to be one of this latter group. I will always be grateful for Bob's enthusiasm, his inclusiveness, and his intellectual generosity.

Science is not only a cerebral endeavor, it is more importantly a human one. Bob instinctively knew that. He embodied high-quality science, adventurous thinking and personal warmth in this role of bringing experimental granular physics to its current place in our intellectual lives.

### **Corey O'Hern, Yale University**

I took first-year physics with Bob at Duke University in 1990 and began working in his research group the following year. I carried out a senior thesis project with Bob that focused on experimental measurements of force fluctuations during steady Couette shear flow. As an example of his dedication to his students, I remember Bob taking several hours out of his day to help me calibrate a set of pressure transducers to measure inter-grain forces in my experiment. Working with Bob and his research group was one of the key reasons that I decided to major in and then pursue graduate studies in physics. During my Ph.D. studies at the University of Pennsylvania, Bob gave a colloquium in the Department of Physics on dense shear flows, and he made sure to emphasize my contributions to the work as an undergraduate during the talk. His glowing attribution of my work greatly encouraged me. Bob's kindness and personal support were rare among scientists. After arriving at Yale as a faculty member in 2002, Bob and I began collaborating on several joint experimental and computational projects involving jamming in granular materials, as well as, co-organizing numerous

scientific meetings. These joint projects continued until he died, and now live on through my mentorship of his former Ph.D. students and postdocs. Bob was an optimistic, open, and creative scientist, and was one of my strongest advocates. I deeply miss him.

### **Jeffrey Olafsen, Baylor University**

Bob Behringer was never old. For the many of us who knew Bob, I'm sure the more well-read of his students and colleagues thought he had *The Picture of Dorian Gray* hidden away somewhere in his attic. However, unlike the protagonist of Oscar Wilde's novel, the only vices that Bob portrayed were those for which there is no sin to have in abundance: generosity, kindness, selflessness, and a willingness to listen. Even after graduating from his research group with a Ph.D., I would continue to speak with Bob at every stage of my career. He made the time to listen and his advice always spoke directly to the point of the issue. There were no wasted measures with Bob and his counsel was always valuable. Both our physics community and the world at large were better for his presence and his absence is sorely felt.

### **Luis Pugnaroni, CONICET / Universidad Nacional de La Pampa**

From a remote location in Argentina, Robert P. Behringer was to us only an iconic name in all those papers we hold close to inspire our daily work. But being ubiquitous, Bob also reached the south and revealed himself as a humble colleague till then hidden to us behind a prolific career. We eventually came together, thanks to our shared friend Lou Kondic, to do research. It was sad to co-author a paper with Bob only after he passed away. It was unique to have had the opportunity.

### **Ryohei Seto, Wenzhou Institute, University of the Chinese Academy of Sciences**

Our paper in this collection is indeed a follow-up to a very recent discussion with Bob at the KITP. His presence was so vivid, and it is hard to believe we cannot continue this discussion with him. I really miss him; he was a great scientist and great person.

### **Mark D. Shattuck, The City College of New York**

Reading all of these tributes, a clear theme emerges: Bob loved physics and made so many important advances, but equally important, he did so with warmth, humor, generosity, humility, and kindness. I can think of no better tribute to

a mentor, colleague, and friend than to say that the scientific community and all our lives were better because Bob was part of them.

### **Abhinendra Singh, The University of Chicago**

My first memory of Bob goes back to May 2010, where I met him at a conference in Dresden. I learned a great deal of science reading his wonderful papers and much more while interacting personally. Besides being very smart and intelligent, he was extremely big-hearted, gentle, and passionate in helping others which made him one of a kind. I met him in April 2018 at KITP, where he very generously took time out to discuss shear jamming and force chains. His work and the unique personality will always be an inspiration for me.

### **Joshua Socolar, Duke University**

Bob was a wonderfully effective advocate for nonlinear science and soft matter physics at Duke University and beyond. I am particularly grateful for his co-founding of our Center for Nonlinear and Complex Systems, which immediately conducted the faculty search that brought me to Duke, and for the support he provided me as a junior faculty member. Bob's tireless efforts to bring exciting researchers in for seminars, conferences, and extended visits had a big impact on science and engineering at Duke and around the world. He helped both the Duke administration and the American Physical Society appreciate the importance and coherence of a broad array of related subfields, and he was a driving force in encouraging inter-departmental interactions and collaborations. His success in mentoring students and postdocs speaks for itself (with ample evidence found in the contents of the present collection), and to his sincere interest in providing opportunities to young scientists in North Carolina and around the world. Bob played his leading roles with admirable humility and consistency, and both his scientific and organizational efforts were remarkably productive. I miss him as a colleague, and we at Duke continue to be inspired by his vision for the sciences of soft matter and complex, nonlinear systems.

### **Stephen Teitel, University of Rochester**

When I think about Bob, I think of a scientist who was totally down to earth, focused on real phenomena, yet at the same time willing to engage with the abstractions of a theorist. Two examples illustrate what I mean. As a theorist I like to think of granular systems in terms of two different types of particles: frictional and frictionless. Bob would

always refer to these instead as frictional and fictional. As a theorist interested in shear flow, I model uniform, steady-state, linear shear flow. However such a thing can be hard to realize in the lab. If one uses a linear Couette cell, particles may fall off the end of the table before one reaches a steady-state. If one uses an annular Couette cell, so as to be able to strain indefinitely and reach a steady-state, the velocity profile becomes nonlinear and nonuniform stresses develop. So Bob designed a new annular shearing cell in which the substrate consists of a series of concentric annular "conveyor belts," the velocity of each being separately controllable so as to enforce a linear (or any other) velocity profile. Bob will be greatly missed.

### **Brian Tighe, Delft University of Technology**

Of course, I'll remember Bob for the science. But the science is so good, it speaks for itself. I'll remember Bob for his understated and avuncular style. He was the kind of colleague and mentor we should all, on our best days, hope to be. "So here's a dumb question..." he'd say, and then he was off. He made the subtle seem simple. He made suggestions that felt like shared ideas. And he could disagree without being disagreeable.

Bob was welcoming. The scientific community that Bob built around himself was one that sought a deeper truth, of course, but it also felt open and friendly and human. When I first started at Duke, Bob made it feel safe to ask questions. And years after I'd moved on, he made me feel like I still belonged. I suspect he was that link for a number of us. I am very, very grateful, and I will miss him.

### **Antoinette Tordesillas, University of Melbourne**

"Hi, I'm Bob," said a voice from above. It was 2005. We were at the Kennedy Space Center, Cape Canaveral, in a NASA meeting on granular materials in lunar and Martian explorations. I had just endured a long, delayed flight from Melbourne and was becoming one with my chair when Bob had interrupted a much needed transition to REM. It took a few moments to realize I was awoken by the man behind those iconic images of force chains I flashed at every public science lecture back in Australia. "I'll send you a bill for that...", a cheeky remark that was trademark Bob. That was the beginning of many cherished memories of times spent with Bob and his wife Sue. Inspiring discussions on science, scribbled with a pen perpetually chewed over, came with much shared laughter and stories of family adventures around the globe. Phone conversations were often turned into impromptu piano recitals, so not even distance and time difference could mask his generosity of spirit. Thank you Bob for the gift of you. I miss you so so much.

### **Devaraj van der Meer, University of Twente**

To me, granular physics is one of the most wonderful fields to work in. The focus lies entirely on the progress of science, and it is not about clashing personalities and rivalling opinions, as in many other communities. I strongly believe that this is the legacy of how Bob Behringer did science. He was not only welcoming to everybody in the field, but treated each idea, each result, and each contributor on whatever level with the same great respect and scientific scrutiny. Next to wonderful discussions we had, I above all just miss the reassuring certainty of Bob's presence, and am grateful for the many things he has accomplished for our field. He will live on in our granular community, which he helped shape and build. He was a scientific giant. We are missing him tremendously.

### **Eric Weeks, Emory University**

I first met Bob in the mid-1990's at an American Physical Society's Division of Fluid Dynamics meeting when I was a graduate student. His first experiments I recall learning about related to Taylor-Couette flows, and then I later fell in love with his photoelastic disk experiments. Even though I worked on neither Taylor-Couette flows nor granular

materials, Bob still took the time to get to know me, and gave me informal advice over many years. In 2007 my group started experiments using emulsion droplets to mimic photoelastic disks, directly inspired by the work of the Behringer group. One of my high points was presenting this work at an APS meeting with Bob in the audience, and receiving gracious comments and questions from him. He was equally insightful with questions and comments related to projects farther afield from his own work. I miss his friendly and thoughtful presence at conferences, and it is a sign of his leadership how many other friendly and thoughtful people at conferences have connections to Bob.

### **Declarations**

**Conflict of interest** The authors declare that there are no conflicts of interest.

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