Profile of Jacob N. Israelachvili

Biochemical engineer Jacob Israelachvili can occasionally be coaxed into giving after-dinner talks about his favorite hobby, the history and philosophy of science, based on his fountain of knowledge on this subject. Since his school days, he has enjoyed reading historical accounts and biographies about history's greatest scientific minds, including renaissance men like Galileo, scoundrels like Benjamin Thomson (aka Count Rumford) who mixed science with political intrigue, and quiet and underappreciated thinkers like Josiah Gibbs, the first American to receive a Ph.D. in engineering and one of Israelachvili's favorites. All these scientists have provided him with a sense of amazement and inspiration, not to mention many entertaining tales.

Someday, roles may change, and Israelachvili may himself be the topic of a future science history aficionado. After a distinguished research career in Europe and Australia, Israelachvili has been a professor of chemical engineering at the University of California, Santa Barbara (Santa Barbara, CA) for the past 20 years, studying the various interactions between molecules and surfaces, principally in a liquid environment. His work in determining the theoretical basis and dynamics of forces that contribute to friction, fluidity, adhesion, and repulsion has wide-ranging applications in areas including medicine, geology, and food science. Israelachvili has designed or improved several instruments that enable direct force measurements as well as authored the definitive textbook on this field, *Intermolecular and Surface Forces*, in 1985 (1). In 2004, he was elected to both the American Physical Society and the National Academy of Sciences for his research contributions.

Of all of the particles and surfaces Israelachvili has examined, however, one of the most mundane, water, has remained the most mysterious. "It's so small and simple and common, and yet it's very complicated," he says. Especially complicated is water's hydrophobic effect. "When water gets next to a surface that doesn't offer it a hydrogen bond or charge to interact with, it doesn't like that surface and causes all such surfaces to come together so the water can get away from it," he explains. The mechanisms behind this surface force interaction, despite being long-studied, are still not completely understood. In his Inaugural Article in this issue of PNAS (2), Israelachvili presents a summary of recent direct force measurements of hydrophobic surfaces in water and discusses how these analyses are beginning to elucidate answers to the mysteries of water.

Jacob N. Israelachvili

A Fluid Youth

Israelachvili was born in Tel Aviv, Israel, in August 1944, to parents of Polish and Georgian ancestry. He would not have the opportunity to spend much time in his family's adopted homeland, however: At the age of 7, his parents sent him to England for boarding school. "The reason they sent me to England was because my father was sufficiently well off," he says, "and at that time it was a sort of snobbish thing to do if you could afford it." Israelachvili took to boarding school quite well, and the English school system, which tended to encourage students to specialize in a particular discipline early on, helped him begin his science studies quickly. "Already then I knew that I wanted to do physics or engineering," he says. "When I was younger I was always making things out of sticks and stones, since we didn't have Lego and Mechano back then."

After completing his secondary education, Israelachvili returned to Israel to fulfill his mandatory military service. Subsequently, eager for more English tutelage, he enrolled at the University of Cambridge (Cambridge, U.K.) and studied physics within the Natural Sciences Tripos, Cambridge's undergraduate program requiring students to study a broad class of sciences before specializing. After completing his undergraduate degree in 1968, he continued his graduate work at Cambridge's Cavendish Laboratory under David Tabor, a renowned experimental physicist.

"Tabor had a profound effect on me in ways that are difficult to describe," says Israelachvili, "because it was more psychological or subliminal." He recalls that Tabor took a Socratic approach with his students, giving them their independence and asking them questions to help guide them instead of telling them what to do. Importantly, Tabor never tried to influence his students. "It seems old-fashioned now, but in Europe there used to be this idea that there were various schools of thought among professors, and if you had a famous professor, all the people in his group were sort of his disciples," he says. "It was understood that they believed what he believed. Tabor wasn't like that."

Israelachvili's dissertation under Tabor entailed measuring the van der Waals forces between surfaces, for which Israelachvili built a device enabling him to measure the forces for surfaces in air that were separated by as little as 15 Å, assessed down to the angstrom level (3). This research was the first time such measurements had been developed over that range and accuracy. Israelachvili's device would eventually be termed the surface force apparatus (SFA) and would become a valuable tool for measuring the attraction and repulsion forces between surfaces. "At that time though it didn't have a name. It was just something I built to get a Ph.D.!" he says.

Over the next several years, Israelachvili did not use the technique he had helped pioneer, as he embarked on a varied research path in tune with the Tripos education he had received. After receiving his Ph.D. in 1971, he remained at the Cavendish laboratory for 2 years performing postdoctoral research on friction and the shear strength of materials. Afterward, he moved to the University of Stockholm (Stockholm, Sweden) as a European Molecular Biology Organization (EMBO) Fellow. In Stockholm, he began working on the molecular motions of lipids and biological membranes, shifting into the realm of biophysics. This switching of fields was not a voluntary choice; the matter was essentially forced on him by financial considerations and other external factors. "But looking back on it," he says, "it was wonderful, because those were my formative years with which I would have been maybe doing the same thing all my life, which I'm glad I didn't."

This is a Profile of a recently elected member of the National Academy of Sciences to accompany the member's Inaugural Article on page 15739.

PROFILE

Magic of H_2O

In 1974, Israelachvili headed to Australia to begin his third postdoctoral position, at the Australian National University (Canberra, Australia). There he returned to his earlier work of studying surface forces, although he then shifted from an air to a liquid environment, an inspiration that stemmed from unusual findings about the nature of water that were making waves at the time. "Water seems to have this cycle where every now and again people say it has magical or strange properties. Cold fusion would be an example of that, or the idea that water has memory. Well, back then there was a raging controversy about polywater," he says. The polywater saga began in the late 1960s when a Russian scientist, Boris Derjaguin, proposed that if water was heated and then passed through quartz capillary tubes, it could polymerize and take on astonishing properties. "It could essentially become a gel or even a solid at room temperature, if you did it just right," Israelachvili says.

Because the surface forces of water apparently induced this phenomenon, Israelachvili decided to investigate and designed a new SFA that could measure force interactions in liquids. Up to that point, researchers had only measured forces in a vacuum or air. He found that under these so-called special conditions, water behaved just like a normal liquid (4). Soon, the work of other skeptical researchers uncovered the "dirty" truth: All the observed changes in water's properties associated with polywater were simply due to contamination with biological and inorganic substances, such as tiny pieces of silica gel that rubbed off capillaries.

Those first tests soon led the way to a long series of experiments measuring forces between surfaces and liquids, which Israelachvili found more stimulating than his previous work with forces in air. "Air is sort of boring, because you can't do much with it. You can't change the pH or the ionic strength of air; you can just change the vapor. But with liquids, suddenly you could change so many things," he says. Many other liquids could be tested besides water, and for each one, various parameters such as salt concentrations, pH, and temperature could be altered to help identify subtle changes in the forces. Israelachvili notes that this area grew rapidly at the time because computer simulations robust enough to handle complicated liquid interactions, such as Monte Carlo interactions, were being developed. As he continued these studies, he naturally progressed to looking at biologically relevant surfaces, such as receptor–ligand or antibody–antigen interactions, which added additional layers of complexity. "Now the surfaces don't have to be symmetrical, as usually happens in nonbiological colloidal systems," he says, "and you have also new types of biospecific interactions."

One set of measurements in particular provided quite a research impact. In 1980, together with colleague Roger Horn, Israelachvili measured oscillatory forces between surfaces due to solvent structure (5). The forces shifted from attraction to repulsion with a periodicity relative to the size of the solvent molecule, but Israelachvili and Horn spent a long time measuring these forces before realizing what they were seeing. "It took a while for, as the English say, the penny to drop," he says. "We were getting results all over the place, and it didn't make sense. We thought we had contamination, but there was no indication of that. Finally we saw it. . . . Oh, you can have a graph with points all over the place." Israelachvili and Horn had expected their data to form a straight line or a curve, but they did not realize a decaying sine wave could fit the data perfectly. "It was an exciting observation," says Israelachvili, who still cannot believe it took so long to find such an obvious solution, "but it also brought home to me how scientifically prejudiced I am even though I think I'm open-minded."

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Other Side of the Ocean

Israelachvili's studies on surface forces in liquids truly engrossed him. He had originally moved to Australia with the intention of staying only 2 or 3 years, but instead he stayed 12 years. With his two daughters grown up, his family faced a decision. "We thought, 'Do we want to stay here forever?' Australia was a great place, but it was very isolated," he says. They had initially decided to return to Europe, and Israelachvili began looking for positions there, but soon after he mentioned his desire to relocate, he was approached by the University of California, Santa Barbara. The university was expanding its engineering department and wanted Israelachvili to join the team. "When I heard this, I said, 'But I'm not an engineer,' and they said, 'Well, yes you are! You've been doing work that is considered engineering in America,'" he says. He agreed to visit the university and was impressed by the department and the high quality of staff being brought in, as well as being charmed by the weather. In 1986, he joined the university's Department of Chemical Engineering.

Coming from a European and Australian background, Israelachvili admits he was a bit surprised by the American research and funding system. "It's still a shock to me," he says. "One is more of an entrepreneur here." In Europe, an institute or university usually receives a block fund distributed internally, but in the United States, Israelachvili must apply for his own funds. Although this process added a "sink or swim" mentality to his work, he soon found that it provided for a more collegial atmosphere, which was unexpected. "I can freely collaborate with other professors, because we're not really competing for the same funds," he says. "Whereas other places I've been, where everything is internal, you know if you get some more money, then someone down the corridor is not." And, while the U.S. system provided less financial security, it also held more promise. "Here, people can have little, but the sky is the limit. In other places, there is a clear limit," he says.

Israelachvili took advantage of the collaborative atmosphere in the United States and broadened his research scope over the past 20 years. "I've had the chance to develop my work much more than ever before and look at fundamental forces and interactions in all sorts of different systems," he says, "and I've done both very practical work for companies as well as fundamental studies." A small sample of the diverse research areas on which he has touched includes studying the flow and friction of chocolate and mayonnaise, how geckos are able to climb up vertical surfaces, the recovery of oil from the ground, and the interactions between lipids and myelin that cause the membranes in the CNS to swell in autoimmune diseases such as multiple sclerosis (6–10). "I think that's been a novel approach for people working in the clinical field to think of these changes in terms of physical forces," he says.

Afraid of the Water

Polywater and water memory may have been relegated to the realm of science fiction, but one mysterious property of water remains entirely true: the hydrophobic effect. "Hydrophobic interactions are one of the last [water properties] that are not fully understood," says Israelachvili, "even though it's been 50 years since people have measured and written about them, because they seem to be a subtle type of interaction involving the structure of water that's different than anything that's really a bond." He notes that water's near-unique configuration of having four hydrogen bonds per molecule gives it the special ability to both repel and herd nonpolar surfaces, leading to one of the strongest and most important biological interactions. Regarding this dual ability, he says, "It's the reason proteins fold and membranes hold together, and unlike a covalent or ionic bond, which has a directionality to it, the beauty of this interaction is that it's strong but allows things to remain flexible. It's why cells can deform easily yet the membranes remain intact."

In his PNAS Inaugural Article (2), Israelachvili summarizes some of the work he and others have done in measuring the forces between hydrophobic surfaces. Hydrophobicity has been difficult to model because it requires a multitude of water molecules, and each one is complicated in its own right. Israelachvili explains that water has a feature known as proton hopping, where protons jump between molecules, complicating the system even more.

Still, experiments using an SFA and atomic force microscopy have shown that hydrophobic interactions exhibit both short- and long-range effects. Long-range effects can span as much as 3,000 Å, although Israelachvili suggests that only short-range attractions under 100 Å represent a true hydrophobic effect. However, he also believes that once two surfaces approach a molecular contact distance (≈10 Å), a force even stronger than the short-range attraction takes over, although reliable data from such short distances have not yet been collected. Continued measurements may soon provide the answers, however, and should Israelachvili decipher the basis for the hydrophobic effect, it will surely make for some nice after-dinner conversation.

Nick Zagorski, *Science Writer*

1. Israelachvili JN (1985) *Intermolecular and Surface Forces* (Academic, London).
2. Meyer EE, Rosenberg KJ, Israelachvili JN (2006) *Proc Natl Acad Sci USA* 103:15739–15746.
3. Israelachvili JN, Tabor D (1972) *Proc R Soc London Ser A* 331:19–38.
4. Fisher LR, Israelachvili JN (1979) *Nature* 277:548–549.
5. Horn RG, Israelachvili JN (1980) *Chem Phys Lett* 71:192–194.
6. Luengo G, Tsuchiya M, Heuberger M, Israelachvili J (1997) *J Food Sci* 62:767–812.
7. Giasson S, Israelachvili J, Yoshizawa H (1997) *J Food Sci* 62:640–652.
8. Autumn K, Sitti M, Peattie A, Hansen W, Sponberg S, Liang YA, Kenny T, Fearing R, Israelachvili JN, Full RJ (2002) *Proc Natl Acad Sci USA* 99:12252–12256.
9. Israelachvili J, Giasson S, Kuhl T, Luengo G (1996) *Proceedings of the Third International Symposium on Evaluation of Reservoir Wettability and Its Effects on Oil Recovery* (Univ of Wyoming, Laramie, WY), pp 1–4.
10. Hu Y, Doudevski I, Wood D, Moscarello M, Husted C, Genain C, Zasadzinski JA, Israelachvili JN (2004) *Proc Natl Acad Sci USA* 101:13466–13471.