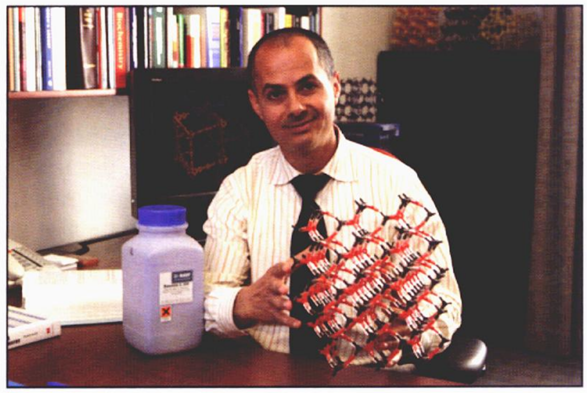
Interview

Omar M. Yaghi: Pioneering the Field of Reticular Chemistry

Alex N. Capecelatro



Dr. Omar M. Yaghi is the Christopher S. Foote Professor of Chemistry and Biochemistry at UCLA as well as Director of the Center for Reticular Chemistry at the California NanoSystems Institute. Professor Yaghi received his B.S. in chemistry from the State University of New York-Albany (1985) and his Ph.D. from the University of Illinois-Urbana (1990) with Professor Walter G. Klemperer. He received his postdoctoral training at Harvard University with Professor Richard H. Holm. His current research is focused on using molecular building blocks to design and synthesize new materials. Professor Yaghi is internationally renowned for his pioneering work in this field, which he calls Reticular Chemistry. His tenacity to create has lead to cutting edge research and the formation of hundreds of new materials, now being employed for applications ranging from hydrogen storage to CO_2 capture.

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One of UCLA's most innovative and influential thinkers, Dr. Omar Yaghi, is today the Christopher S. Foote Professor of Chemistry and Biochemistry. Although he has taught at three top tier universities in a fifteen-year span, Professor Yaghi has had a unique trek to the top. He was born in Amman, the capital of the Hashemite Kingdom of Jordan, in 1965. Brought up in a large family of thirteen, Omar has ten brothers, three sisters, and he sits fourth from the bottom in age (Figure 1 features four of them). Born into a middle-class, hard working family, Omar naturally felt a need, from a very early age, to be independent. He exemplifies this trait by reminiscing, "I was a weird child. When I was growing up, in my third grade, I decided that I would not have my parents tell me what to do. I told them that I will do my best in school and that they have no right to look at my grades."

"Naturally," Yaghi recounts, "my grades should be okay." This attitude is very characteristic of Professor Yaghi. He does not like people telling him what he should do, and by that token, he earns the respect of colleagues by routinely out-performing even the pros. This independence left Yaghi ready to take on any challenge. At the age of fifteen, his father decided that it would be best if Omar left home and continued his education in America. He initially refused, not wanting to be told what to do, and feeling it important to finish school in Jordan. But he has never been able to let a good opportunity go to waste, and Omar eventually gave in to the attraction of the U.S. He accepted the offer and was soon shipped to Albany, New York. The area was home to Omar's uncle and brother, making it a comfortable new home. He resided, however, with a nice older couple that introduced him to the American way of life and the kindness of its people.

Omar started his American education at a community college, having to prove himself from scratch. It didn't take long for his grades to show potential, and soon Omar was transferring to the State University of New York (SUNY) Albany. Omar remarks about American education, "The system is terrific, it doesn't ever stop you from realizing your potential."

It was there, at SUNY Albany, that Omar Yaghi got his first real introduction to chemistry. The ambitious student quickly found himself doing research with three professors. The research positions were attained by simply asking professors who taught his classes, a technique Yaghi suggests to undergraduate students today. He started broad, working on a theory project, a physical chemistry project, and a biophysical chemistry project. Yaghi recalls, "I was a student that was very interested in chemistry. I guess my captivating experience in the field was when I saw a stick and ball diagram of water and methane molecules in my preparatory school book, then later when I took an organic chemistry lab." He remembers the joy of taking a solution, doing a reaction, and producing beautiful crystals.

The pleasure in producing remarkable materials from a simple synthesis led to Yaghi's eventual Ph.D. study. Still gratified by the American education system, Omar explains, "The most amazing thing was that I applied to graduate school and I got a telegram that said, 'We will pay you twenty-thousand dollars and you may study Ph.D.' And I thought, wow, this is unbelievable, that I will actually get paid to study for a high degree. And so I ended up at University of Illinois-Urbana Champaign."

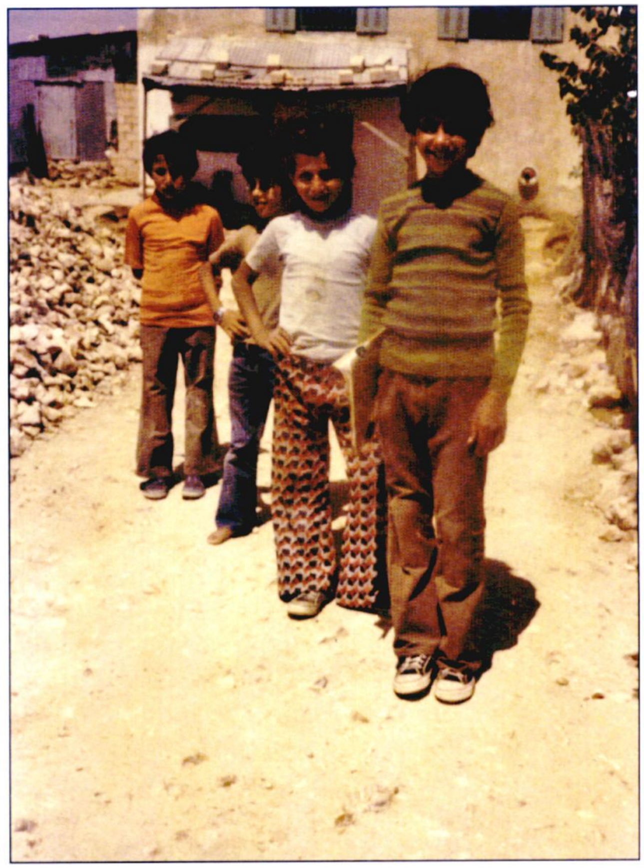

Figure 1. *From left to right: Ali, Abdul Fattah, Mohamed, Omar (carrying study papers). The background is the Yaghi dwelling linked to a cattle residence (in Arabic: "Yakhoor"), and the rocks are assembled from an olive and grapevine orchard.*

It wasn't by pure happenstance that Yaghi attended UI. He recalls, "I was flipping through the University of Illinois' pages and discovered Professor Walter Klemperer's page. There he had a beautiful molecule that looked like a sphere, almost like a buckyball, but made of a metal oxide. It was then that I thought, this is what I want to do." Yaghi's academic career has ever since involved the construction of beautiful, elegant, and novel structures. Similar to the structures of Walter Klemperer, Yaghi has created many aw-inspiring structures. Two examples, found in Figure 2, are ZIF-105 and ZIF-100 (zeolite imidazolate frameworks), extended structures designed for applications in clean energy. These structures were crafted by graduate student Bo Wang.

Even as a graduate student, Omar was just beginning to figure all this out. He reflects, "When I was a graduate student, the way I made some of my compounds was by just mixing chemicals together, which was great. I would just mix two things, and what came out were wonderful materials. I was fortunate that what I made was really a one of a kind material or compound. It encouraged me to be more of a discovery type chemist. But, it didn't satisfy my intellect in the sense that there was no intellect in mixing A and B. What would have been this shake and bake or stir and wait, as we used to call it, was fun because one discovered new things, but I realized that the importance of the work is going to be in terms of rationalizing what you made, or in terms of designing new materials. So I felt that that was lacking in inorganic chemistry. I became very interested in the idea of stitching building blocks together to make new structures that would predetermine blue prints, so to speak. So then my interest in building blocks took me to do a post doc at Harvard with Dick Holm."

Yaghi's Postdoctoral fellow lasted from 1990-1992, and helped construct the ideas for his first professorship. He was given the task of extracting clusters from a 3-dimensional network and acquiring the building blocks. The building blocks could not easily be produced by other techniques. The reversal of this idea, taking building blocks and assembling them into new extended structures, was Yaghi's proposal when he started working at Arizona State University in 1992. Many doubted whether Yaghi's proposal was even possible, but he persisted. His students were soon making microcrystalline materials, but had difficulty moving forward. "It didn't come easy," he began, "but we did it. I had to tell my student that he needed to take the microcrystalline material and make single crystals. He said that it is too hard to do and it doesn't work, and so I said, if you can make crystalline material, you can always make single crystals of it too." Yaghi humorously continues, "I am going to chain you to the bench. You are going nowhere until that [crystallization] is done. I don't know whether by fear of torture or by love of chemistry, it got done. That is sometimes how science works." In a playful way, Omar Yaghi is terrific at working with students and getting them to achieve results they never believed possible.

Yaghi believes that determination and perseverance are essential: chemistry is an endless sea of possibilities and wonders, thus it makes sense to believe that whatever chemical construction one thinks of (if grounded in sound scientific thinking) should yield to those willing to pursue it. This mindset won him the American Chemical Society-Exxon Solid-State Chemistry Award in 1998, an award given to researchers making breakthroughs in solid-state chemistry.

Realizing that he was making major breakthroughs in science and his research environment could be made stronger, Yaghi transferred to the University of Michigan in 1999, becoming the Robert W. Parry Collegiate Chair. He made the move because Michigan offered better instruments and facilities, allowing his lab to operate at its optimal level.

For these same reasons, Yaghi moved to Los Angeles in 2006 to become the Christopher S. Foote Professor of Chemistry and Biochemistry at UCLA, as well as the Director of the Center for Reticular Chemistry at the California NanoSystems Institute (CNSI). He remarked, "UCLA offers a lot of advantages over many other schools. It is part of one of the greatest university systems in the world. That is not to say that UCLA doesn't face challenges, likes any other university, but these challenges can be overcome. Overall, I think UCLA is an excellent environment, the people I have met here are wonderful people, and there is a lot of rich, scientific research going on." The same year he started at UCLA, Popular Science magazine announced Yaghi as one of the "Brilliant 10" in science and engineering. His work at this time was achieving international acclaim, as the importance of his creations was becoming clearer.

The first breakthrough that launched Yaghi's success was the invention of metal-organic frameworks, or MOFs, as they are known in the field. MOFs consist of very open extended structures, with a metal at each joint, and an organic unit as the struts. These organic-inorganic hybrid materials have unique characteristics and superior properties. After MOFs came the discovery of COFs, or covalent organic frameworks. COFs are made entirely of organic building blocks, which typically link through carbon-carbon bonding. One of the more recent discoveries, zeolite imidazolate frameworks, or ZIFs, were a long time dream of Yaghi's. He explains, "I would often suggest [ZIFs] to students and they would always blow me off. Maybe they didn't believe it would work. So finally, after 5 years of

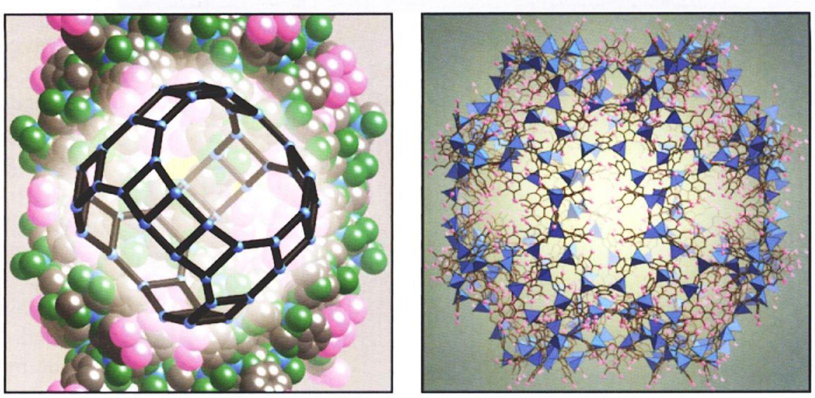

Figure 2. *ZIF-105and ZIF-100, two of the many elegant extended structures created in the Yaghi lab.*

suggesting this to students, who always blew me off, I decided enough was enough. I said to myself, I will go into the lab, and the first person I meet, I will demand they do this reaction. And it was [Kyosung] Park (former graduate student), the nicest guy, charming guy, and essentially he had to put up with my demand. I said [jokingly], 'Park, you will do this reaction and at the end of the week, you will report on your result. And if you don't do it, I will not talk to you.' And it worked! That now has started a whole new area of porous materials that we call ZIFs."

Along with MOFs, COFs, and ZIFs, Yaghi has imagined and designed numerous other materials. He calls the new emerging field of linking molecular building blocks, Reticular Chemistry. The field has already created hundreds of compounds, all of which are well characterized and can be easily varied. There are now at least one hundred research groups around the world in academia, industry, and government labs doing this kind of chemistry. According to Yaghi, this is the fastest growing area in chemistry, the number of materials and diversity are unparalleled by any other.

With the exciting expansion of this field in a relatively short time, Yaghi is currently working with industry collaborators on finding and pursuing profitable applications. Yaghi describes one of the properties of MOFs, "Some of the structures we made have extremely high surface areas. For example, MOF-5 (Figure 3) has optimized surface area of about 3300 m^2/g. That means that if you could unravel the structure of MOF-5, it would cover 3300 meters squared for each gram." These materials have potential in gas storage, such as ethane and hydrogen.

Right now, Yaghi's materials can store between 7.5-12% hydrogen, by weight, at 77 Kelvin. According to Omar Yaghi, the Department of Energy requires 6.0% by weight by 2009, and if Yaghi's group can figure out a way of storing that much hydrogen at room temperature, they will open the door to using hydrogen as a fuel source. It is calculated that 4kg of hydrogen

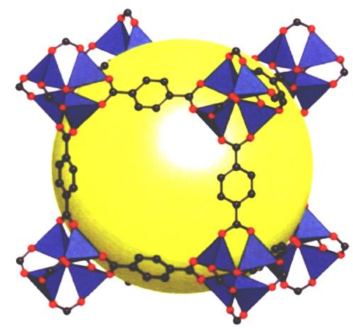

Figure 3. *MOF-5 has an optimized surface area of about 3300 m^2/g.*

are needed to fuel a car for 500km, which at room temperature would fill a sphere of about 5m in diameter. Yaghi's approach is simple: use a material with an exceptionally high surface area, modify its surface to be "sticky" for hydrogen, and you can begin to pack more molecules into a smaller volume. "It's similar to stacking cars in a car pack," says Yaghi.

The problem of methane storage has already been solved. Because methane has a C-H bond, which is stickier than hydrogen, they have been able to devise a MOF suitable for the job. By packing the material into a fuel tank, automobiles running on the compressed gas can double in range. This technology is being marketed by BASF (Badische Anilin- und Soda-Fabrik), a chemical manufacturing company based out of Germany.

BASF has recently increased their collaboration with Omar Yaghi through cooperation with CNSI. UCLA is, as exemplified by Yaghi, a very exciting place for research. There are many ways for a student to get involved, Yaghi explains, "If I was a student interested in science, I would say, nothing really is impossible. If you have an idea, it is worth pursuing. Very soon you will realize whether it works or not. But pursuing the idea is enough to uncover opportunities you have not imagined. That is really at the heart of being a scientist and at the heart of inventing new things. For example, today one of the most urgent problems facing humanity is achieving clean energy. Renewable energy. How do we come up with a renewable source of energy? There are tremendous scientific challenges. These challenges probably will not be solved if we continue the current pace of progress. They are, however, becoming urgent problems. So what we need are people who will discover new materials that put us on different ground. These discoveries will be made by people who are creative and unafraid to pursue their ideas, all the while having the attitude that it will work. That is my

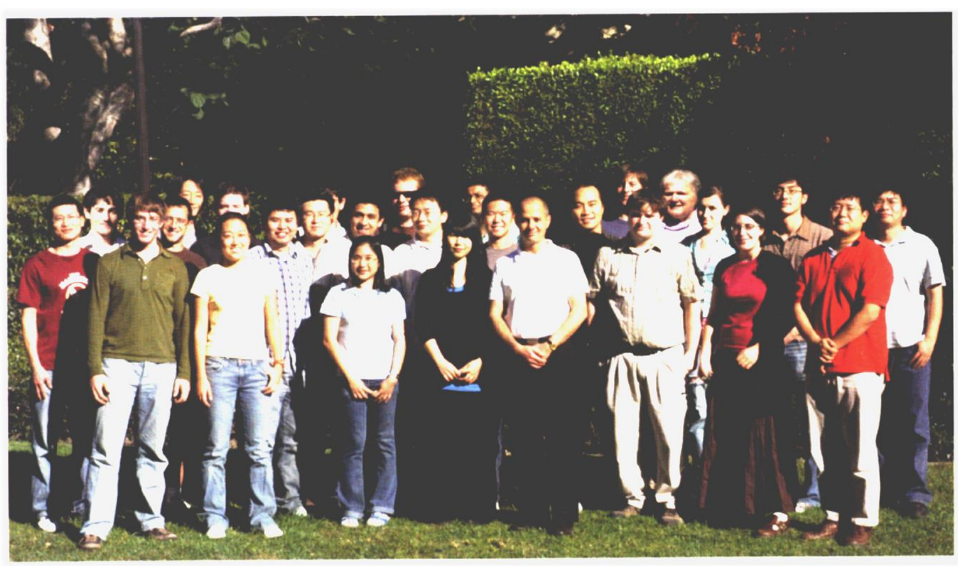

Figure 4. *The Yaghi Group, 2008.*

advice to younger people. Pursue your ideas. Keep your eyes open for what your investigation might uncover." A handful of brilliant scientists pursuing their ideas in this realm are already hard at work, earning their degrees from Omar Yaghi. The Yaghi research group is pictured in Figure 4.

Yaghi suggests that all interested students should get involved in research. He adds, "The prerequisite is that the interested person be open minded to learning new things, and that is the only prerequisite. The opportunities are there, especially in a large university like UCLA. You don't just have one professor active in research; you have many of them working on cutting edge projects. These provide you with those open doors to test your own ability and to act on your ideas. Collaborate with graduate students and post docs. Learn about science. Learn about how scientists think. Learn about what are the problems facing society."

It is important to get involved, suggests Yaghi, while always remembering that many individuals are out there to help. Throughout his career, Yaghi has had invaluable help. "Many people," Yaghi remarks, "have helped me along the way, including wonderful students that I have had. It would be too long of a list to enumerate. Nothing can be developed," Yaghi continues, "with the magnitude of Reticular Chemistry by just one person alone. Although it is based on a simple idea, it involved many people along the way. Collaborators, such as Professor Michael O'Keeffe from Arizona State University and Dr. Ulrich Mueller (BASF) have been essential to my success. Discussions with such collaborators have been invaluable. Another person, whose contributions are not insignificant, is Dr. Ron Allain, who used to be the CEO of Nalco chemical company. He has become the liaison in my group bridging academia and industry. He opened my eyes to the fact that you can be an excellent professor doing scholarly basic research, but you cannot be a great professor unless you also use that basic knowledge to address societal problems. My career, thanks to these wonderful people and of course my valued students and postdoctoral fellows, has been very rewarding."

Professor Omar Yaghi, a giant in his field, has come a long way from his independent childhood. Entering a new culture, discovering his own interests, and repeatedly persisting, Yaghi has paved a monumental path. While entering new territory, Yaghi has created materials that even nature had not produced. He often stumbles across obstacles, determines a way to address them, and keeps pushing forward. He has set up collaborations, made an alliance with industry, and is determined to answer some of society's biggest questions. Where can a man named one of the year's "Brilliant 10" go from here? At age 43, Yaghi has many years to answer that question. While the specifics are unknown, one thing is for certain, Omar Yaghi will continue to invent and impress in uncharted territory.