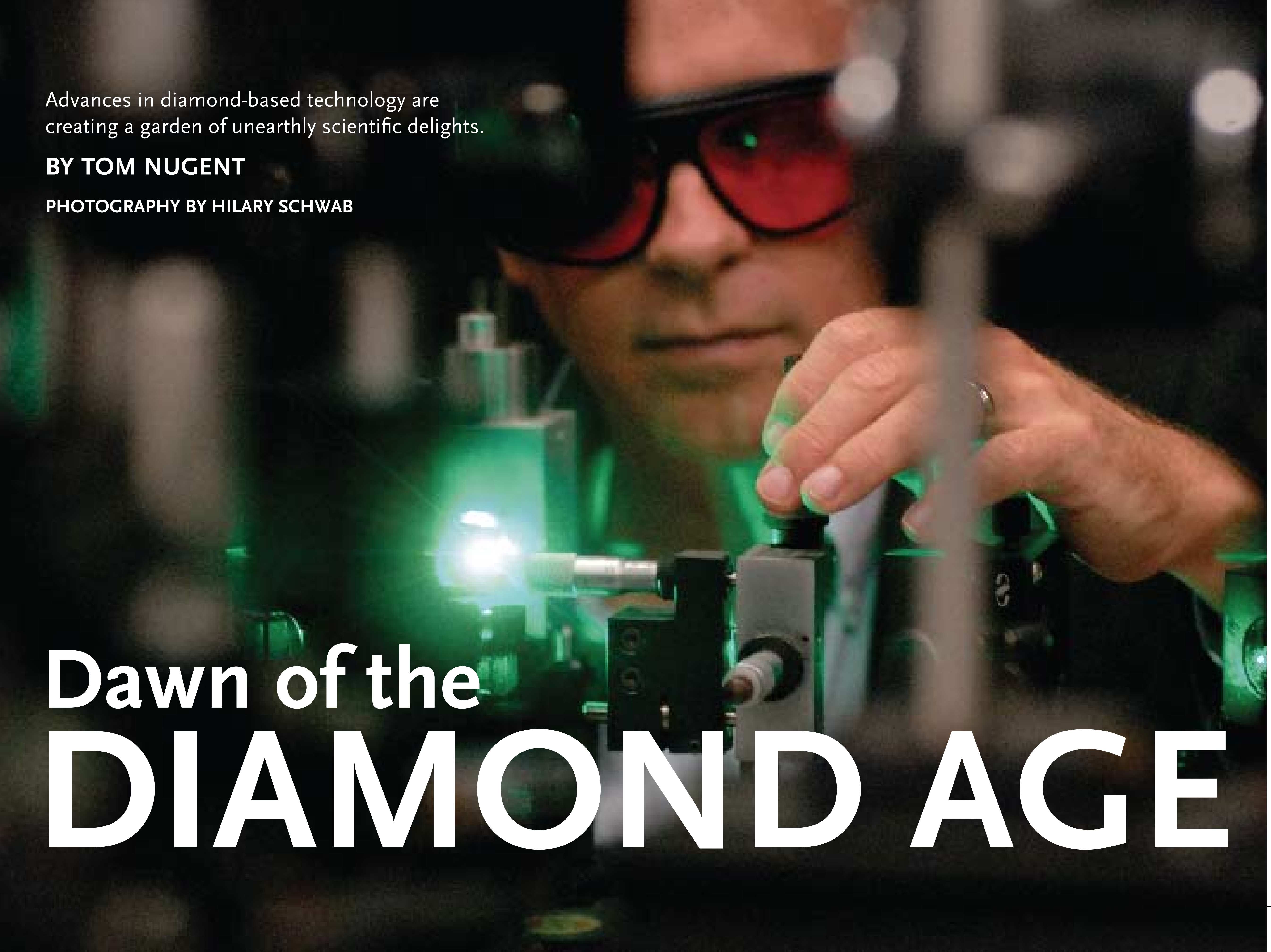
Advances in diamond-based technology are creating a garden of unearthly scientific delights.

**BY TOM NUGENT**

**PHOTOGRAPHY BY HILARY SCHWAB**

# Dawn of the DIAMOND AGE



**Hemley aligns a laser for high-pressure spectroscopy on a sample inside a diamond-anvil cell.**

**RUSSELL HEMLEY '77** often rides to work on a battered 15-speed Fuji bike that he picked up at a yard sale for $25, and he keeps a conga drum from his days at Wesleyan in his office. And yet, Hemley lives in a "high pressure world"—though not in the usual sense.

The pressures in his world can exceed those found at the center of the Earth. His scientific research takes him to a realm where materials are entirely different—atoms and molecules collapse to form new solids, minerals take on new structures, ice has 20 different forms, and gases can become superconductors.

Drop by Hemley's lab at the Carnegie Institution in Washington, D.C., and you might find him aligning laser or x-ray beams with samples contained within diamond anvil cells, devices that in recent years have allowed scientists to explore this exotic world more fully.

Hemley calls this work "alchemy," a deliberate reference to the quixotic and unsuccessful attempts by early experimenters to transmute elements into gold. Hemley's modern-day alchemy ventures into uncharted territories, with unknown rules, where everyday substances we know and understand here at the surface of our planet behave in highly unusual ways.

Among the more astonishing results to emerge from his laboratory is an entirely new way to make high-quality diamonds. Years of painstaking work achieved what many had thought would be impossible: making diamond crystals from gas. Described as a significant advance, this breakthrough technique enables the production of extra tough diamonds within a matter of hours. It seems certain to have a huge impact on science and industry alike in future decades—and quite possibly on the tightly controlled commercial diamond market.

The Carnegie Institution hosts a small enclave of scientists, post-docs, and selected students working in a hilltop cluster of buildings that border Washington's bucolic Rock Creek Park. Since 1905, one of its departments, the Geophysical Laboratory, has been a center for the study of high-pressure phenomena, driven at first by a desire to understand the Earth's formation and structure.

"Go ahead, take a look!" said the congenial Hemley one afternoon last May, handing his visitor a gleaming cylinder about the size of a beer can. "Do you see those little jaws at the bottom? They're made of diamond, and they're gripping a little chunk of the earth—a little piece of silica—with about two million atmospheres of pressure.

"That's the kind of pressure you find in the core of the Earth. We've been studying what goes on in that region for many years. When we first compressed this sample of silica, we were interested in whether or not all this and related minerals would become metals, or 'metalized,' at pressures of the Earth's core—starting just above one million atmospheres. Early on, scientists had proposed that idea, but our experiments showed that it isn't true.

"That's a good example of how we're trying to learn new things about the interior of the earth, along with other planetary bodies—by studying how different materials respond to regimes of high pressure and high temperature. This is a wonderfully exciting field to work in, because so little is currently known about what happens to ordinary substances like gases, water, and rock under these extreme conditions."

Hemley, now 52, has gained an international reputation for his cutting edge research in high-pressure physics and chemistry since he was hired as a post-doctoral fellow at the Carnegie's Geophysical Laboratory in 1984. He became a member of the scientific staff in 1987.

During the past 24 years, he has won numerous awards and prizes (in 2005 the prestigious $800,000 Balzan Prize in Mineral Physics) for his discoveries of how rocks, minerals, and other planetary materials behave under the awesome pressures found within planets, from Earth to Jupiter. The author of more than 450 scientific articles (including 52 in the authoritative *Physical Review Letters*), Hemley has also studied what he calls "pressure alchemy": how solid materials such as sulfur and even gases such as oxygen can be turned under pressure into metals and superconductors. Nitrogen can be turned into a semiconductor like silicon. He has studied how organic molecules behave under extreme conditions and examined the prospects for life in the outer solar system, for example, on the moons of Jupiter.

Hemley has sought to understand how hydrogen behaves under the ultradense conditions in the interiors of the solar system's largest planets. What happens to this fundamental material, the most abundant element in the universe, under extreme pressures? This is one of the unsolved problems in modern physics. When Hemley's chosen field was in its infancy during the 1920s, at the birth of quantum mechanics and modern physics, scientists predicted hydrogen would metamorphose to metal under these conditions, and since then, there have been numerous calculations postulating disparate properties for hydrogen's high-pressure phase, including superconductivity well above room temperature and superfluidity. Hemley has been investigating this unresolved enigma for years, and many of his papers in *Physical Review Letters* have described unanticipated discoveries along the way.

His work not only contributes to understanding the fundamental properties of matter throughout the universe, but it also has important applications in the day-to-day world. For example, high-pressure materials science has opened important areas of research in storage of hydrogen as a non-polluting fuel.

Despite his impressive record of achievement, if you ask him to describe the goal of his life's work, Hemley might surprise you with his understated assessment. "What we do here, in the broadest sense," he says with a thoughtful smile, "is to look closely at the 'energetics' of matter. Much of the matter in the cosmos exists under extreme conditions of pressure and temperature. We're finding out what happens when you move those atoms and molecules closer together or farther apart.

"What's been extremely exciting and important for this whole field in the last 20 years is the way we can vary these conditions over a wide range, and then watch the unfolding of different physical properties. I came to Carnegie because it's the world-leading facility for this area of physical science, and I haven't been disappointed. We lead various multi-disciplinary teams, and we share facilities with large national laboratories, such as Argonne (Illinois), Brookhaven (New York), and Oak Ridge (Tennessee)."

Richard A. Meserve, president of the nonprofit Carnegie Institution, says Hemley's research has often led to thrilling discoveries.

"Rus is an exceptionally talented scientist," says Meserve, "and he's been remarkably inventive [in developing new tools] that expand our understanding of the universe. And I think that's really a big part of why he's made so many major discoveries that have impacted mineral physics over the past 20 years."

Adds Dave Mao, a close Carnegie colleague who has worked on numerous projects with Hemley over the years: "Rus is extremely resourceful as a scientist, of course, and he's also very courageous. He's not afraid of taking on something because it might be too difficult or too big. Not at all! Once he decides to work on a project, he never lets up.

"On the other hand, he refuses to take himself too seriously. We get together once a week to discuss new ideas and concepts, and those sessions are really enjoyable. Rus always brings the white wine and I bring the red, and the rest of the crew brings the cheese. We sit around and we talk about the various things we've been working on.

"We also spend a lot of time laughing, which says a lot about the kind of attitudes that Rus and I and the others all bring to work."

**"RUS IS AN EXCEPTIONALLY TALENTED SCIENTIST," SAYS MESERVE, "AND HE'S BEEN REMARKABLY INVENTIVE."**

**THE SON OF A PROMINENT** geologist for the U.S. Geological Survey, Hemley grew up in California, Colorado, and Utah. At Wesleyan he concentrated on philosophy at first.

"What I soon realized," he recalls with a nostalgic chuckle, "was that philosophy depended heavily on the boundaries of science. In other words, I saw that the kinds of questions you can ask with the hope of a clear and useful answer depend on what you know about the natural world through scientific processes.

"After a while, it seemed to me that a quicker way to understanding would be through science itself. I chose chemistry because I thought it could be a springboard to all the other sciences. It's curious that this ultimately led me to another kind of 'alchemy.'

"After searching for a program for some time (and bumming around Europe with a backpack one semester), I was very fortunate to major in chemistry and find a mentor in the chemistry department who had just arrived on campus from Harvard," he remembers. "The late Professor Bryan Kohler was setting up a laboratory, and he very kindly gave me a chance to help him. He was a tremendous inspiration and really reoriented my thinking. Though I was only a junior, he treated me, and his other undergraduate group members, as full members of his team of graduate students and post-docs. He encouraged us to believe that we could change the world with discovery."

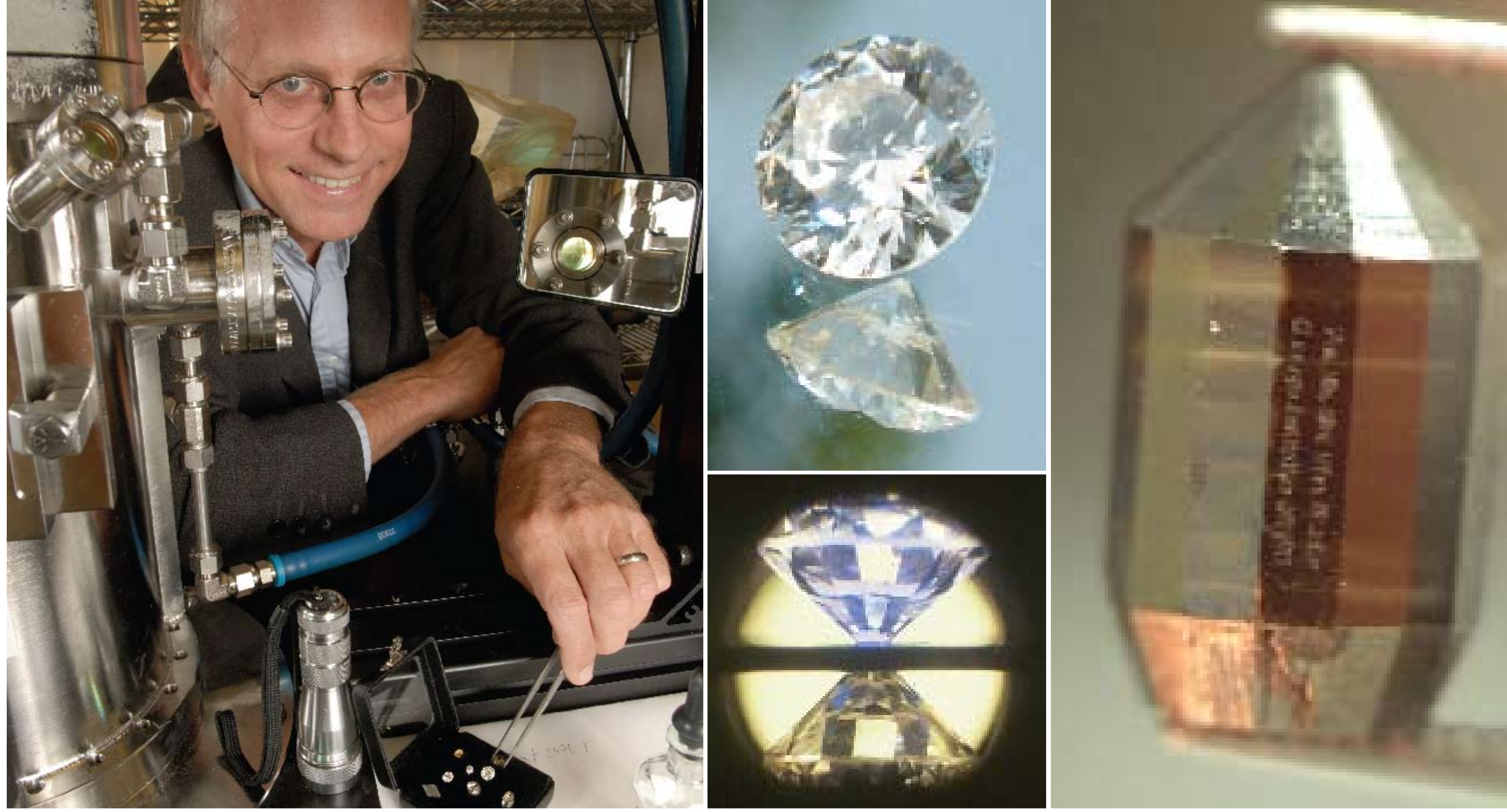
Before Hemley graduated, he had written two papers with Kohler that were published in scientific journals. Kohler then steered him to Harvard, where he obtained a Ph.D. in physical chemistry.

Hemley says he still remembers the excitement he felt while trying to crystallize beta-lactoglobulin with retinol in order to model the photochemistry of the retina of the human eye. He was having trouble crystallizing the protein from store-bought milk, so he stopped by a dairy farm near the Connecticut river for fresh milk.

"Then I raced back to the lab and I crystallized *that*. I spent weeks and weeks on that project," he says, "and it was a wonderfully exciting time for me. It was nice to be able to do that kind of research in a relatively small college environment where you are around researchers getting their Ph.D.'s in chemistry.

"Wesleyan had—still has—a Ph.D. program in chemistry. That's one of the things that make it a really special place, in my view. The thrilling time I had working with Bryan Kohler, combined with the support from the other terrific professors in the department, made my Wesleyan experience far greater than I ever expected."

Hemley says he also had lots of fun on campus. "I kept that conga in my freshman dorm room at West College, and I used to jam with others at all hours of the day, and even took African drumming at the Center for the Arts, which had just opened. It was 1973, at the tail end of the wild, protest years at Wesleyan."



All in a day's work: Hemley examines diamonds made by chemical vapor deposition in the adjacent chamber. (Center top): gem-quality diamonds from the lab; (bottom) a diamond anvil cell; (right) a 12 mm long diamond single crystal from the lab.

These days, this Carnegie scientist, who has taught as a visiting professor at both Johns Hopkins University and the École Normale Supérieure in Lyon, France, plows through 10-to-12-hour-days working on "exciting science projects that I love to wrestle with."

"I still enjoy the humanities," he adds. He just completed a short scientific biography of Erskine Douglas Williamson, a Carnegie scientist from Scotland who did fundamental work in physics, chemistry, and geophysics during World War I, but was little known because he died prematurely, at the peak of his powers, in 1923. The research led to the naming of a building at the University of Edinburgh for Williamson two years ago, and a summary of his life, based on the speech Hemley gave at the dedication, was published in *Physics Today* a few months ago.

The ever-present research challenge for Hemley is to reach even higher pressures. On the cosmic scale, the pressures that can be achieved in the laboratory today are orders of magnitude lower than those at the centers of stars. His work with making diamonds out of gases may help push back the boundaries of the high-pressure universe by creating more powerful diamond anvils.

Synthetic diamonds have been around since the mid-'50s, and diamond has been made from gases, but as polycrystalline films—not single crystals. Hemley's work was unique in one crucially important way: he created the first large, super-hard, single-crystal diamond using a new high-speed (and thus relatively inexpensive) technique, known as "chemical vapor deposition," or CVD. The diamonds are made out of a cloud of superheated hydrogen and methane gases in a device that resembles a high-tech microwave oven.

In principle, the technique could be used to make inch-size wafers and blocks of perfectly pure diamond.

"Diamond has extraordinary properties, including an amazing ability to transport heat and high transparency to light, Hemley explains. Potentially, diamonds could be used to make computer chips far faster than the silicon chips used today.

"As I sometimes like to tell audiences when I give talks about our work in CVD diamonds and high-pressure physics here at Carnegie: 'The Diamond Age is upon us!'"

And what about the lucrative diamond market? Some analysts believe the retail price of "a girl's best friend" will plummet by up to two-thirds within the next decade, as synthetics increasingly invade the traditional diamond market.

Doesn't he want to capture a piece of this market and perhaps get rich?

"We're scientists," he says with a chuckle. "We take the long view. We want to push this new diamond technology, which could be the basis of entirely new industries. We don't have any plans to start selling gems. But of course...the gem diamond market *is* artificially controlled, and I wouldn't be at all surprised to learn that the cartels which controls it are starting to get a little worried about the work that's been going on in our lab."

***Tom Nugent is a freelance writer whose work has appeared in the* New York Times, People *magazine, and* Stanford *magazine as well as many other publications.***