Physics is the broadest of all studies, sweeping from the universe’s grandest creations down to the particles that form particles that make up atoms. Given such a large vista, the physicists at the Colorado School of Mines have research agendas that are surprisingly close. As Mark Lusk, a Mines physics professor put it: “We’re all interested in the properties of very small particles, where the quirky nature of quantum mechanics is in full force.”

It’s just that what these particles have to say about nature covers a huge range of topics. Lusk is most interested in how electrons move around in, say, solar cells or the proteins of microbes. His colleague Jeff Squier crafts photons to illuminate the black gearboxes of living machines. Lawrence Wiencke and Fred Sarazin are interested in individual charged particles carrying as much energy as a tennis ball smashed at 50 miles per hour. In the lingo of particle energy, Mines physicists study a range from $10^{-10}$ to $10^{20}$ electron-volts (eV). That’s 30 orders of magnitude, or roughly the difference between something happening once in the history of the universe and something happening a trillion times each second.

Like Lusk, Lincoln Carr focuses on the low-energy side – on atoms and molecules a million times colder than outer space, specifically their quantum behavior. Carr, too, is a theoretical physicist, a conceptual designer of the foundations for technologies we can’t yet imagine. His Meyer Hall office spots an orange-leather couch above which are festooned the prayer-flag-like results of a student project.

When Carr arrived at Mines in 2005 from the University of Colorado at Boulder–JILA – one of the world’s top atomic, molecular and optical physics institutions – Mines had a very limited theoretical physics program. That has changed quickly; now there are several highly research-active theoretical physics faculty members and as many as 20 graduate students doing theoretical physics work, some of it at the highest levels. For instance, recent Mines PhD graduate Michael Wall won the 2014 Nicholas Metropolis Award for Outstanding Doctoral Work in Computational Physics from the American Physical Society, the top such award in the world.

Carr’s philosophy echoes that of the growing theoretical physics team: “I want to create great students and colleagues.”

Taking high performance computing, Physics Professor Mark Lusk is exploring structures such as C70 fullerenes (below), molecules consisting of 70 carbon atoms, as all-organic solar cell materials. C70 fullerenes can be encapsulated within a framework of linked carbon-based molecules and then exposed to light, excited electrons (dark green) jump to the fullerene lefthand edge, leaving positively charged regions on the framework (brown and magenta). The quantum mechanical motion of the photons and electrons can be mapped out in detail, allowing researchers to relate sunlight intensity to the resulting electrical current before creating a material in the laboratory. Projects like this provide insights into how electrical changes occur in theoretical physics and symbolic chemistry.
Across the hall is the Carr lab. Its hardware is comprised of a dozen desks, coffee and espresso machines, a microscope, whiteboards plastered with equations and a roll-of-history's greatest physicists. Black-and-white files of standard office paper, looking down from on high. Here, some of Carr’s group works on a widely used open-source code to model quantum states of matter: DMRG. Lusk’s office paper, looking down from on high.

In Carr’s lab, his couch is just as much a conversation piece as the lab’s hardware. In the middle is a small, color TV, and in front of it are bunches of stuffed animals - a pair of scuba gear, a stuffed elephant, and a model of a B-52 bomber. Carr’s couch is a popular spot for graduate students and visitors, and it has been used for hundreds of studies around the world.

A key research thrust is the development of a theory of many-body systems of ultracold molecules. In the 1980s, Eugene Wigner and Albert Einstein hypothesized that a cloud of millions of atoms could, if cooled to temperatures close to absolute zero, collapse into a single “supersolid” exhibiting strange quantum properties at a macroscopic scale. Carr’s group is now trying to predict how a cloud of ultracold molecules might interact — a much more complicated task, given that electrons and nuclear spin states of each atom in the molecule as well as the overall rotational, vibrational and other degrees of freedom come into play. Carr has calculated that an ultracold cloud of ethyl fluoride (CH$_3$F) trapped in a crystal of light could lead to quantum magnets with properties much different than those hanging on refrigerators.

“I spend a lot of time on this couch just dreaming where it can go,” Carr said.

Lusk, who frequently collaborates with Carr, sees supercomputers as the quantum behaviors of molecules. He is the lead theorist of the Renewable Energy Materials Research Science and Engineering Center (REMSRC) as well as lead scientist of the Global Energy Computing Organization (GEco). Lusk’s work focuses on quantum transport — the way in which energy and charge can be scattered around in these very small structures, “as if put to random walk in collaboration with Alex Seliger, an associate professor of chemistry and geophysics at Mines. Seliger has created — “Kooky landing” — carbon atoms held by link-by-link organic molecules in the theoretical design and Seliger had created.


Energy applications are interesting to Lusk, his programs run on IBM’s Blue supercomputer. He also models things like the reaction of energy and electrons in biological systems such as the green algae at Yellowstone National Park.

“At first, we thought their proteins were just structural units holding things in place. But it turns out that they also guide the transport of energy and charge and use a whole grab bag of complex tricks to influence the environment in which the charges and energy find themselves,” Lusk said. “While learning a lot about how to design systems where all the pieces conspire to create something really, really emergent phenomena by those in the business.”

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Photos: Jeff Squier

“Once it’s there, it’ll be manageable enough for a biology lab,” Squier said. “The system is an enhancement of one he co-invented in 1992. Like the original optics, it uses a feedback loop (a thousands of a trillionth of a second) pulses of laser light to capture the action of the inner workings of a living cell, and in ways that present those previously visualized planes and don’t disrupt the target. The new system, first demonstrated 20 years after the original, creates images in six planes of depth at once, offering scientists a view into multiple tiers of cellular activity at the same instant.”

Collaborators at the University of California, San Diego, have used it to look at the inner workings of the brains of fruit flies. Keith Neeves, associate professor of biological engineering at Mines, would like to take closer looks at barbuda cells. The National Renewable Energy Laboratory is interested in using multiphoton imaging to see how exactly what happens as an electron is produced in solar cells. A Spain-grant PhD student is working on a version 10 times smaller.

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Sarazin and Wiencke are members of the International Pierre Auger Collaboration, a collaboration of more than 100 scientists and engineers. They study the nature and origins of ultra high energy cosmic rays, the most energetic particles ever observed. Detecting those energies with a man-made particle accelerator would require superfling (GeV) large hadron colliders. For the sake of research’s cost around the cars. Measurements of high energy cosmic rays represent a unique view of the extreme-universe beyond our galaxy. The Pierre Auger Observatory in Argentina, completed in 2008, aims to study by covering an area of 1,260 square miles (almost exactly the size of Rhode Island), and its giving its dual-detector system a few chances per year to witness such particles in action.

The observatory’s two detection systems are comprised of many many detectors. The system encompasses more than 1,600 tons spread at 1-kilometer intervals, each filled with 3,600,000 gallons of purified water (for the curious on campus, there’s one parked on the north side of Meyer Hall, a stout brown cylinder custom-made in Brazil). Pitch dark inside, solar-powered photomultipliers detect a fraction of the interaction particles “air showers” created when cosmic rays crash atmospheric molecules. Analysis of the data collected by these water tanks is Sarazin’s area of expertise.

“This array of detectors in the statistical engine of the observatory. This is how most of the air showers scintillating over the observatory are detected,” said Sarazin.

A second system, comprised of 27 fluorescence telescopes at four sites view the sky above the surface detector array. These optical detectors collect data on moonless, clear nights. They capture the atmospheric emissions of nitrogen when a cosmic ray particle cascade sweeps across the atmosphere. The effect, though invisible to the human eye, is like a million-pound lightbulb running on an east-west line through the day at night.

Sarazin led the design and installation of the two automatic laser systems that circle the endpoints of the observatory. These solar powered systems fire thousands of collimated light bursts into the night sky. “We use the atmosphere as the world’s largest collimator to measure cosmic rays,” Sarazin said. “The atmosphere is a complex dynamical system. To measure the cosmic rays accurately, the observatory measures air by measuring every eight. Combining fundamental atmospheric, applied with science and engineering as a physicist at Mines, is fascinating.”

“IFR fundamental science,” Sarazin said.”Fundamental science is part of the foundation that lets you do a lot of other things.”

Photos: Jeff Squier