Neutrino Capital of the World

by

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ABSTRACT

Neutrinos are ubiquitous particles, but they don't like to mingle. Each second, billions of them pass through our bodies, slicing imperceptibly through our delicate internal organs. They can barrel through the sun, stars, and planets without a single interaction. Only one in every ten billion of the invisible, chargeless, nearly massless particles will interact through a weak force with another atom, leaving an observable trace of its existence.

But in a small town in western South Dakota called Lead (rhymes with 'need'), a 125-year history of mining ore and gold out of the ground may be replaced by these impalpable particles. Lead was the birthplace of neutrino science when chemist Ray Davis began his work on solar neutrinos over thirty years ago. He installed a tank filled with 100,000 gallons of dry cleaning fluid a mile underground in Lead's Homestake mine and began counting neutrino interactions. Eventually, he earned the Nobel Prize for his work; his surprising results changed the world of particle physics.

Now that the Homestake mine is closed, scientists, politicians and local citizens have converged on this small town with the hopes of turning it into a national underground laboratory that houses experiments ranging from astrophysics to deep subsurface geobiology. In the process, the state of South Dakota has introduced a unique funding scheme in which science is democratic. Politicians, scientists and regular folks play important roles in the neutrino populist movement, working together to preserve a scientific resource and life in a small town.

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According to the banner hanging behind the podium, it's "Homestake Day at the Legislature." A short, bald man walks across the stage of T.F. Riggs High School Auditorium in Pierre, South Dakota. His cartoonish name, Marvin Marshak – just a syllable away from Warner Brothers' alien Marvin the Martian – is in stark contrast to his ordinary appearance: glasses, dark suit, tentative smile. But Marshak may as well be on another planet. He stands in front of a community of South Dakotan legislators, ex-miners, high school students, local businessmen, and a South Dakota Public Broadcasting camera crew preparing to talk about physics. He is an ambassador of science wielding a microphone, a standup comic in an unfamiliar venue.

Marshak, a physics professor from the University of Minnesota, is in the middle of a state known for its ruggedness – a frontier even after the frontier moved further west to oceans and temperate climates. He stands in the Central Time Zone, but is just 20 miles from the line where Mountain Time begins. He and an all-star lineup of scientists have converged on this high school stage to give a three-hour colloquium to a crowd of ordinary folks. The scientists' power point presentations are peppered with Greek symbols, equations, and graphs intended to convince this audience to support a new frontier: the cutting edge of science. But the scientists will learn, too. In the question and answer sessions the audience will probe the purpose and value of their experiments not in terms of scientific merit, but in the context of the local community. The future for science and for South Dakota may lie underfoot in a 125-year old gold mine called Homestake.

The scientists are sure of one thing: they need a National Underground Laboratory in the United States that is deep and large enough to house their experiments, which range from geobiology to anti-nuclear proliferation technologies to plain old particle physics.

South Dakota is sure of another: they are the best site for that laboratory. At this preliminary stage, the lab has even been dubbed the Homestake Underground Laboratory. At one point during the lectures, a woman in the audience shouts out a question to one of the speakers, who has been calling the project NUSEL.

"What's NUSEL?"

"Aha, well that's what we call the National Underground Science and Engineering Laboratory," physicist Harry Miley of Pacific Northwest National Laboratory answers.

"Homestake," interjects a physicist from the University of Maryland standing in the sidelines.

"Homestake – for short," Miley confirms. Chuckles vibrate through the room. Heads nod forceful agreement.

Over the past three years, people from this state have upped the ante in a legislative and financial gamble on a scientific goldmine. The Homestake Mine may, they think, change the fortune of their local universe. The Northern Plains are in uncomfortable flux. Aging and dwindling populations experience "brain drain" as college graduates move out for jobs and doctoral degrees that aren't available or useful. Agricultural decline makes it just a bit harder to eke out a living as a rancher or a farmer each year. In the smallest towns, schools shut down or are simply consolidated at a central location. In its series about "the vanishing heartland," *The New York Times* calls this trend a "slow demographic collapse" in one breath, and "dying" in the next.

South Dakotans indefatigably deny these predictions. Most of the people I met during my visit in January could recall better days, but would never call the towns they love and live in "dead." Nonetheless, a growing number of people are staking hopes for the future on a larger universe above and beyond their big sky. Dark matter, dark energy, neutrinos, and decaying protons might, they think, anchor South Dakota more firmly in the world. Over the past few months the state government has forged daring legislation and volunteered to absorb enormous responsibilities and risks on behalf of basic science that has few discernible real-life applications. In the end, the people (through their legislators) decide whether science has made a good case for itself. The Homestake effort is a kind of grassroots movement that has brought the rough-hewn world of mining closer to the white labcoats of physicists.

It's an interesting experiment.

Western South Dakota is, as anyone who has endured the seemingly interminable, flat drive across I-90 knows, gold country. Signs lure drivers to gold mine tours and shoot-'em-up gambling towns and not much else. Indeed, South Dakota's unlikely relationship with underground science began by chance in a town that was firmly rooted in a very different project: mining. Lead (pronounced leed), South Dakota, was named for its many "leads," veins of gold that prospectors followed in search of a lode of gold ore. Two French Canadian prospectors staked the original claim in 1876. According to local legend, they deemed there was enough gold for them to build homes and retire – and thus named it the Homestake. Newspaper heir George Hearst bought the property and incorporated the Homestake Mining Company in 1877 and the city of Lead, "the mining camp that prospered," grew in the hills surrounding the company's eponymous flagship mine. Over the next 125 years, the mine produced 40 million ounces of gold – today, worth about $400 an ounce.

But in December of 2001, miners detonated the last 1600 kilograms of ammonium nitrate, dumped the last five and a half tons of ore in an elevator called a skip, and hauled it up the shaft for crushing. The rock contained the last 1.1 ounces of Black Hills gold to be produced at a mine that had weathered two world wars and the Great Depression. The gold wasn't gone. There was still more to be found at greater depths. But prices were low and the operating costs of mining 8,000 feet underground were high. The 130-degree rock face at the bottom of the mine had to be kept at a workable temperature by a massive air conditioning system. Tons of rock had to be hoisted a mile and a half for just a few ounces of gold. Mining had to end.

The mine had faced low gold prices before. In 1964, expenses increased as the tunnels (called drifts) extended deeper. The price of gold was fixed while inflation was rampant. Al Gilles, the chief mining engineer at the time, still lives in Lead and invited me to his home between bowling engagements, shocked that any of the few people still working at the mine had known to refer me to him. He said it had been a tough year. "That was about the time when we could use a little outside money. At that time the price of gold was still $35 [an ounce] and everything was going up – supplies, everything else, it was getting tough to make ends meet." That year, the South Dakota legislature intervened on behalf of Homestake by reducing the ore tax. Unionization battles divided the company's miners and engineers. In the midst of all this mucking about, Brookhaven National Laboratory made an unusual proposal.

It came from Ray Davis, Jr., a young chemist who began working at Brookhaven in 1948. In an autobiographical statement, he recalled his arrival at the lab. He was told "to go to the library, do some reading and choose a project of my own, whatever appealed to me." Davis found something intriguing in a 1948 review article by physicist H.R. Crane: "Not everyone would be willing to say that he believes in the existence of the neutrino, but it is safe to say that there is hardly one of us who is not served by the neutrino hypothesis as an aid in thinking." Davis decided that he had to catch this "neutrino." To do so, he would need to go underground.

Though not as famous as its cousins, the electrons or the photons, the miniscule neutrino is an essential ingredient in the universe. Neutrinos participate in the reaction that fires the sun's furnace; these infinitesimally small particles make nuclear fusion possible. Neutrinos pour out of the spectacular supernovae explosions that have furnished our galaxy with its diverse array of elements – including gold. Like baking powder in a cake, neutrinos quietly maintain the texture of the universe, while the chocolate and the icing get all the attention.

Physicists Wolfgang Pauli and Enrico Fermi first postulated the neutrino's existence in 1930. They'd discovered a loophole in an otherwise ironclad law of physics: conservation of energy. During radioactive decay, some of the energy disappeared without explanation. Pauli decided that the missing energy was being carried away by a neutral, photon-like particle that moved at the speed of light and had no mass – a speck of energy. His colleague, Fermi, gave it an Italian name: "neutrino," for little neutral one. "Dear radioactive ladies and gentlemen," Pauli wrote to his colleagues in a coy letter. "I admit that my solution may appear to you not very probable, because if the [neutrinos] would exist, they would have been observed long since. But only who dares wins." Pauli and Fermi committed a kind of scientific sin by concocting a particle no one could detect: Was the neutrino just a helpful fiction or was it a fact? They feared that no one would ever know.

Through the neutrino's adolescence and until the 1950s, the scientific community seemed content to believe in the neutrino for practical reasons. Adding the neutrino into equations made the math work out and kept the general framework of the universe in order.

But scientists are skeptics. Why would they accept a particle they could not detect? Using complicated machines, scientists can "see" small or large things more sensitively, "feel" surfaces down to the electron level, or "hear" vibrations by amplifying signals into the range of ordinary human senses. Neutrinos simply fell outside of the realm of human awareness. Even for scientists armed with an arsenal of expensive machines, neutrinos were ghostly. But not only did they not interact with our senses; they hardly interacted at all.

Physicists knew that objects, particles, people – everything in the universe – interacted through four forces. Two are apparent in everyday life: gravity and electromagnetism. There is also a so-called strong force (a glue that keeps protons together), and a weak force, which controls radioactive decay. Neutrinos were neutral, so electromagnetic interactions were out. As wisps of pure energy, they would be unaffected by gravity. They were also unaffected by the strong force in the nucleus of atoms. Neutrinos only interacted through the weak force, which was active only over very small distances. From a neutrino's point of view, most matter looks like empty space anyway. If you were to model an atom in which the protons and neutrons were a centimeter in diameter, the electrons circulating around the nucleus would be microscopic, and the atom's diameter would extend thirty football fields. As sub-microscopic packets of energy, neutrinos were virtually unstoppable. It would take a light-year's thickness of lead to slow one down.

In 1956, physicists Clyde Cowan and Fred Reines launched an experiment called Project Poltergeist. They detected ghostly neutrinos produced by an artificial source – the Savannah River nuclear reactor in South Carolina. Project Poltergeist was able to confirm the existence of the neutrino at last; Reines later won the Nobel Prize for his work on it. However, the physicists weren't able to capture many of the elusive particles. Their *Science* paper, "Detection of the Free Neutrino: a Confirmation" makes its claims in rather unsettling language. "It was *felt* that an identification of the free neutrino had *probably* been made." The Savannah River reactor produced 10^{13} neutrinos per square centimeter each second. But at its most sensitive, the detector only caught 3 neutrino interactions per hour. Techniques would need to be refined if these finicky, shy particles were to be put to good use.

But Davis was unfazed by the neutrino's anti-social behavior. He became interested in measuring the neutrinos that spewed out of the sun as a byproduct of fusion. Solar neutrinos could become a tool for examining the sun's core with the right kind of detector. Davis and John Bahcall (a theorist who collaborated with him) wrote in *Science*, "One may well ask, Why devote so much effort in trying to understand a backyard problem like the sun's thermonuclear furnace when there are so many exciting and exotic discoveries occurring in astronomy?" After all, scientists already agreed that fusion was the sun's source of energy. Protons collided to form hydrogen, which combined to form helium, heavier elements, and sunshine that lit and heated the earth. But despite widespread agreement, no one could verify the theory because the fiery interior of the sun was invisible to conventional telescopes, which could only record surface activity. Davis' idea was to see into the center by measuring the neutrinos, which arrived at earth just eight minutes after they were produced. Like perfectly preserved fossils, they could tell physicists what life was like in the center of the sun, answering questions about the elements the sun burned and how long it would shine. But there was a paradoxical twist: the clearest view of the sun could only come from deep underground.

A mile of rock is a great aid in separating the wheat (neutrinos) from the chaff (signals produced by other particles). Every second, the earth is bombarded by a riffraff of cosmic particles. Neutrinos make up a formidable part of the stampede, as about 40 billion solar neutrinos pass through an area the size of a fingernail every second. But since neutrinos interact with particles so rarely, their footprints would be drowned out by the tracks of other particles without a shield. A deep mine was the best filter.

The detector had to be large. Although neutrinos were plentiful, they were more likely to barrel through matter than interact. Occasionally, though, they would pass an atom at just the right distance and interact weakly. Just as the chances of winning a raffle increase if you buy more tickets, the chances of finding a neutrino are greater if there are more potential targets. Thus, the bigger the detector, the more atoms lying in wait and the better the odds of detecting neutrinos.

The solution to these logistical problems lay in South Dakota. The Homestake mine was deep and the rock was hard. A large chamber could easily be mined out and secured. It was a fortuitous time for Brookhaven's proposal: gold prices were low and the mining industry needed a public relations facelift, as it was becoming notorious for ruining landscapes and poisoning environments. The mine was persuaded to agree to a contract for the experiment, and rented out a spot 4,850 feet underground. The experiment was designed so as not to interfere with daily life in the mine. Homestake's in-house publication, *Sharp Bits*, boasted, "By placing the room at the end of the tail-drift [tunnel], the excavation, (and later erection of the tank) could be accomplished with a minimum of interference with our normal mining operations."

Even though it was pushed into the margins of the mine, the experiment wasn't unknown. The invisible particle known to the world through blips on a geiger counter or data points in a scientific paper became an important export alongside Lead's traditional output of minerals, ore, and gold. While the neutrinos' appeal wasn't as straightforward as "Black Hills Gold Jewelry: Distinctive! Unique! Beautiful! Striking! Charming!" the particles were a source of genuine curiosity. Many miners appreciated Davis' ability to explain his work in "twenty-five cent words." Bob Harlan, who began working in the mine in 1968 said, "The miners were very aware of the project that was going on in the mine and I think many of them were proud to have something like that being conducted in the mine."

And so, just as nearly everyone in Lead can tell you about stopes and carbide lamps and the "red wagon" (a squat portapotty with a submarine-like lid that moved on rails), everyone has something to say about the old neutrino experiment. Davis started his solar neutrino detection efforts in the 1950s in Barberton, Ohio. "Brookhaven had a chamber somewhere in one of the salt mines. It was only 2,000 feet deep, and it wasn't deep enough. And that's why they wanted to come here, because at 4,850 [feet] they're not quite a mile deep, but pretty close," former chief mining engineer Al Gilles said. The prototype detector in Ohio held 1,000 gallons of perchlorethylene, an ordinary dry cleaning fluid which contains an isotope of chlorine. Like a set mouse trap, the chlorine isotope captured any neutrinos that come close enough. When a neutrino interacted with a chlorine atom, the tiny burst of energy was enough to change a neutron within the chlorine nucleus into a proton. This transformed the chlorine into the next atom up the periodic table: argon, a radioactive gas that could be removed from the tank and measured with a Geiger counter. Counting the number of argon atoms in effect told the researchers how many neutrinos had been snared. But as Davis wrote in a letter in 1960, "The experiment does not represent a serious attempt to detect solar neutrinos. To observe the flux of solar neutrinos now calculated by the astrophysicists would require an experiment using 50 to 200 times the volume."

Al Gilles' neighbor on Sunset Road, Evelyn Murdy, did secretarial work for Homestake for many years and recalled a model of Davis' experiment that was installed in the surface offices. "It was huge," she said, her eyes widening at the memory. She sheepishly retracted her wonder when Gilles pointed out that the prototype Evelyn saw was miniscule in comparison to the detector that was eventually installed underground. In order to make the experiment worthwhile, Davis proposed and built a 100,000-gallon detector. Miners called it "the tank."

In 1964, a large cavern was excavated at the 4850 level. The chamber was 30 feet by 60 feet, with a 32-foot high ceiling. The walls were secured by rock bolts drilled 8 or 10 feet into the wall and attached to cable netting that supported any loose rock. In pictures taken just after caverning was finished, a man with a hardhat stands in a vast empty expanse of space. White rock bolts stud the wall. It looks strangely similar to a picture of a man silhouetted and dwarfed by the immensity of the night sky.

Pete Fuller, who once served as legal counsel for Homestake, had been down in the mine and was eager to take a break from dismantling his Christmas decorations to talk about the laboratory. "I've been in the neutrino chamber. You walk in a big submarine door, like you see in the movies, and you seal the door." Dan Durben, a physics professor at nearby Black Hills State University, assisted the scientists with the experiment right before the mine closed and was amazed at what he saw. Important science was being done on old, antiquated equipment that looked as if it had just been haphazardly cobbled together. Durben reported that the whole setup looked no more sophisticated than the equipment one would find in a 1950s kitchen. "It's vintage down there."

The tank filled the chamber almost completely. It was 48 feet long and 20 feet in diameter, and looked like a giant oil drum lying on its side. The detector was a scaled up version of the early prototype experiment in Barberton. It used the same chlorine isotope traps to catch neutrinos, but had 1,000 times as many traps. The tank was transported down the shaft in small pieces in the same cages that miners took to and from their shifts and was finally welded together in the cavern. "It was indeed an excellent job of welding and tank construction," commented the *Sharp Bits* magazine that chronicled the construction of the detector. The perchlorethylene was produced in Wichita and transported to Lead in ten 10,000-gallon railroad cars. It was lowered into the mine over many trips, in 700-gallon increments. The massive construction efforts enabled Davis to start counting particles: somewhere between two and seven neutrinos per day.

"I think it was perceived as something quirky and weird in the physics community," said Bill Harlan, who worked in the mine, laying track, before becoming a journalist. But not so in Lead. "That neutrino experiment has operated almost continuously since the mid 60s, right through the time the mine closed. So the word 'neutrino' was not new to people of Lead, South Dakota, and people were bemused by it," he said by phone.

Local opinions on the future of particle physics are about as prevalent and strong as ideas about property taxes and gold. They are passed around like gossip. Lillian Hall, a widowed mother of six who lives in nearby Spearfish won't claim to know what a "neutron" is, but knows that Homestake is the ideal site. "I just think it's the most feasible spot in the world because it's so deep," she said by phone. Although her statement isn't precise, like a rumor that circulates and grows less factual with each repetition, it is the right idea. Homestake's main advantage is its depth, which shields experiments from cosmic radiation and provides a unique environment in which to study subsurface geology.

Some take offense at this sort of simplification. James Patterson, a former physics professor at the South Dakota School of Mines and Technology, wrote an editorial complaining that "the issues have already been presented (locally) in such an oversimplified way as to be misleading." In Patterson's view, the emphasis should be on South Dakota's potential to do good physics, not on popularizing the neutrino. Like celebrity personalities that are ossified by magazine profiles that list their hopes, dreams and favorite colors, neutrino science has become rather overgeneralized in the hands of the South Dakota media. Pete Fuller described the extent of local knowledge: "People can tell you what it is. It's a subatomic particle! They're bombarding us!"

This type of knowledge is vague, and decidedly more enthusiastic than accurate. But such outbursts clearly show that the public has grappled with the science. "Neutrino" is part of the vernacular in Lead. There are few places in the world where one could walk into the dentist's office, the grocery store and the post office and meet people who even recognize the word neutrino, much less talk about it on a regular basis. In 2001, Wick Haxton came back from South Dakota exhilarated by local interest. A proposal that he submitted to the NSF boldly claimed, "We suspect it is no longer possible to find any student in the Lead area over the age of eight who was unaware of solar neutrinos." Rose Emanuel, a physics teacher at the Lead-Deadwood High School confirmed the proposal's audacious statement: Kids knew the word "neutrino," even if they were fuzzy on the details. In contrast, most of my college-educated friends had never heard the word.

Al Gilles proceeded through an explanation of the experiment slowly, and was careful to get things right by drawing on his technical knowledge and memory: "The tank was 100,000 gallons of – they used perchlorethylene because the chlorine atoms is what the neutrinos would then convert to argon. And then I don't know how often, but once every six weeks they would bubble helium through the tank and that gathered up the argon particles and then they put that material into their, what do they call it, I guess you would say the detector." Bill Harlan put it this way: "People here as a rule don't subscribe to *Physics Today*, but they do understand the neutrino research."

Gilles and I talked about neutrinos, the mine, and life in Lead at his dining room table, which was dominated by the neat clutter of holiday crafts. After his cuckoo clock sang four times and I prepared to leave, he shoved folders of information across the table toward me. There were collections of articles clipped from popular science literature, technical journals and newspapers. Each piece looked as if it had been carefully read and neatly maintained. Key ideas were flagged by flurries of marginalia. "The…experiment is located deep underground in order to shield the experiment from the background of cosmic rays that can cause spurious signals" is underlined in a wobbly pencil. In the middle of a graph showing data from the Homestake experiment, a question mark corkscrews down in front of error bars and data points labeled "predicted" and "actual." In another packet of carefully filed articles, a diagram shows cosmic rays streaming down from space, a row of boxes called the "surface air shower array," and a big cylinder underground labeled the "liquid scintillation detector." But a handwritten arrow points to an area between all these elements. In the midst of this cosmic schematics is the "TRAILER ABOVE PARKING LOT AT HOMESTAKE."

"I think these articles will be of interest to you," Gilles said as he flipped through the documents, some labeled with his name and the date he received them in neat cursive. Two houses down, at Ivo and Evelyn Murdy's small house on Sunset Road, Evelyn collects stories science and mine stories from the local newspapers and sends clippings to old friends who have left town. My grandmother, who grew up in Lead, now forwards the packages on to me.

The articles indicate that Davis' first published findings in 1967 set off tremors through the particle physics world. Homestake was at the epicenter of a crisis. The tank did not catch enough neutrinos – only about one-third as many as expected. In his book

Exploring the Sun, Karl Hufbauer described the physicists' range of reactions. "Davis was delighted. Nothing is quite so satisfying to an experimentalist as coming up with a result that challenges theory. By contrast, Bahcall was disappointed by the failure of his prediction." As Bahcall told sociologist Trevor Pinch in an interview 20 years later, "The thing we most worried about this experiment, in funding it, was that it was just a pipe dream of astronomers and they'd measure nothing." In fact, they'd measured more than nothing, but only enough to raise more questions – about the detector, the theory and the neutrinos. Many scientists thought there was something wrong with the experiment. Indeed, even the idea of Davis' daily commute in a "cage," an elevator usually packed with 40 grubby, wisecracking miners traveling 30 miles per hour straight down to a dirty, humid day of work was foreign to most scientists. And pictures of Davis in hard hat and button-down shirt studying a valve the size of his head with a stern, quizzical look hardly elicit a convincing picture of discovery.

At Homestake Day at the South Dakota legislature, physicist Ken Lande (who worked with Davis) gave the South Dakotan audience a short lecture on local neutrino history. "What happened?" he asked a silent audience. Why was the tank catching so few neutrinos? Was it experiment? Was it theory? Was the Sun dying inside, sputtering like an engine without enough gas? "Either the experiment was wrong or the model was wrong or the neutrino didn't do what it was supposed to," Lande said. The experiment was renewed and fine-tuned, and continued taking data much longer than anyone – scientists or miners – would have predicted at the outset. But the fine-tuned measurements found even fewer neutrinos. A 1972 article in *Science* said it all in the title: "Solar Neutrinos: Where are They?"

The Homestake results were eventually confirmed by a number of international neutrino projects: GALLEX in Russia, Gran Sasso in Italy, Super Kamiokande in Japan and SNO in Canada all helped flesh out the neutrino's identity. The Homestake finding prevailed. Neutrinos were unexpectedly slim pickings.

Meanwhile, theorists began to work up possible explanations for the astrophysicists, particle physicists and cosmologists who now had a stake in the neutrino puzzle. Physicists had mapped a neutrino family tree consisting of electron neutrinos, muon neutrinos and tau neutrinos. Each type interacted with matter in a different kind of reaction. Davis' detector, filled with chlorine traps, was only sensitive to the electron neutrinos that were produced in the sun. Theorists, puzzled by the consistently low solar neutrino measurements, began to consider the possibility that Davis' results were actually correct. If so, the electron neutrinos produced in the sun could be unstable, like radioactive elements that decay. A solar neutrino traveling out of the core of the sun might be able to shapeshift into something else that was invisible to the detector. Perhaps the missing electron neutrinos from simply changed into muon or tau neutrinos somewhere between the sun and the earth. Physicists began to think that neutrinos were schizophrenic.

"They're kind of intriguing characters, aren't they?" asked Kate Scholberg, an MIT physicist who studies neutrinos at the Super-Kamiokande detector in Japan. "Neutrinos that participate in a particular interaction have a particular flavor," Scholberg explained. In the case of fusion in the sun, electron neutrinos are produced, but detectors on earth saw far fewer electron neutrinos than were expected. In 2001, the Sudbury Neutrino Observatory (SNO) in Canada, which was sensitive to all three flavors, found that other neutrino flavors were arriving along with the electron neutrinos. It was convincing evidence that the solar neutrinos were switching identities mid-journey.

Like all "particles," a neutrino has particle-wave duality. It exists as both a point in space and as a wave of energy, depending on how it is measured. Each neutrino flavor (electron, muon, tau) is a wave with a characteristic shape. But each individual flavor of neutrino is also a mixture of the other types, so a neutrino is a packet of different waves with different frequencies, some choppy and some calm ripples. As the group of waves that make up the electron neutrino travels from its birthplace in the center of the sun to the earth, its identity may change depending on which wave is dominant. Scholberg explained it to me in terms of a neutrino made up of two different kinds by resorting to music. "Eee oooohhhh eeee oooooohhhh eeee ooohhhh," she sang in her high voice. At any moment, the neutrino could be an electron neutrino ("oooohh") or either a muon or tau neutrino ("eeee"). It's a little like eating a swirled ice cream cone. Each bite is dominated by a different flavor, even if a spoonful has a bit of the other flavor in it – vanilla, chocolate, or strawberry neutrino.

At a recent talk, Scholberg impersonated an oscillating neutrino again. "You can do a little dance to understand the mixing," she explained to a room of amused physicists. She stuck her arms out perpendicular to her body and jumped up and down, tilting from side to side. When her arms were parallel to the floor, she was an electron neutrino. When they were waving up at an angle, she was a muon or tau neutrino. The neutrino is always wiggling among states.

Davis' work at Homestake uncovered what Scholberg called "the famous mystery of the disappearing solar neutrinos." The solution to the mystery was far more complex than physicists anticipated, and Homestake played an important part in revealing the particle's true, rather wobbly identity. Scientists didn't have to revamp their solar models or redesign their directors – they just had to reimagine neutrinos. In order for Scholberg's "neutrino dance" explanation to hold true, the particle must have mass and travel slower than the speed of light. But those ideas didn't hold with particle physics' main theoretical platform, the so-called Standard Model. Perhaps the discrepancy between the old theory and the new result is most apparent in John Updike's verse, which was written before neutrino oscillations were discovered:

> Neutrinos, they are very small.
> They have no charge; they have no mass;
> they do not interact at all.
> The earth is just a silly ball
> To them, through which they pass
> Like dustmaids down a drafty hall.

Neutrinos are, indeed, small and chargeless. The poem's popularity among physicists indicates they may be granted the poetic license to "pass like dustmaids down a drafty hall." But things have changed since Updike wrote the poem. Neutrinos do have mass and they do interact.

Physicists are still arguing about what to do with the obsolescent Standard Model. What will fill the gap: string theory, grand unified theory, dustmaid theory? "Physicists," Gilles observed, "aren't anxious to change [theories] unless they're positive." In 2002 Davis shared the Nobel Prize for his discovery, which physicist Kevin Lesko called the "big shift, the paradigm shift in our understanding of the universe." Ken Lande, who lived in Lead with his family for many summers while collaborating with Davis, often directs public attention to the important role that Homestake played in this drama as he canvasses for the scientific drama to continue in a new underground lab. "The…thing that happened here in South Dakota in the Homestake Mine, it started a brand new field: this is the field of neutrino astrophysics. So, it is worth remembering."

Just as Davis was winning his Nobel Prize, the mine that had served as his laboratory was in its death throes. Mining is a destructive business, and companies spend years attempting to erase their footprint on the environment: cleaning the land, the water and the mine itself. Gilles' house looks out over a deep canyon once filled with activity. There's the number five winze airshaft, the area where the cutting-edge tube conveyor (brought all the way from Japan) used to run, the grain elevator-like Ross shaft where cages sped underground. "It was a tough duty when they were starting to tear [the mill buildings] down," he said, describing the loss of a huge complex built into the hillside on the edge of town. "Everything you knew for a lifetime, they were tearing off the mountain. That was kind of discouraging." Later, on our way to dinner we passed the bare hillside in the Murdy's pickup truck. Gilles pointed out the ruined foundations where massive machines once stomped ore to a fine powder. Everyone sighed.

South Dakotans reluctant to abandon Homestake have put their support behind the particle they helped mine from obscurity. "Neutrino: A particle whose time has come" and "Neutrinos, they're not just for physicists anymore" are examples of the sorts of headlines that have peppered the local newspapers since the mine announced it was closing. *The Rapid City Journal*, which serves the western half of the state, has run 143 articles about neutrinos over the past three years even though it has no science section. In contrast, *The New York Times* has mentioned neutrinos in only 15 articles over the same time period. Charles Lamb, president of the South Dakota Academy of Science made the minute particles a priority in his inaugural speech among other important issues like cloning, biodiversity, climate change and space. The numerous, but hard to detect Lilliputians of the particle zoo have become the mascot for the proposed underground laboratory and for South Dakota's future.

Two weeks after the Homestake mine announced it was closing in September of 2000, excited scientists proposed it as an ideal site for a multipurpose underground laboratory – an Earth Lab and a center for particle physics experiments. Deep in the mine, few cosmic rays would interfere with measurements. Geologic knowledge had been accruing at Homestake over the past 125 years, and an extensive collection of core samples and other data was filed away in huge wooden cabinets and drawers in the Homestake buildings. These would provide a rich archive for Earth Lab.

It was also an ideal time for science to take up residence in the mine: The experienced workforce of miners was eager for jobs, and an extensive network of shafts, tunnels and fiber-optic cables were in good shape. At that time, a flurry of activity occurred in neutrino science, as experiments around the world confirmed that neutrinos were shapeshifters. As an undergraduate physics student doing summer research at the University of Washington in 2001, I sat through many presentations about neutrinos and Homestake: the future of particle physics research. The Homestake Mining Company offered to donate the mine as a laboratory, with the stipulation that they be freed from "future liability that might result from the construction and operation of the new laboratory" according to a proposal by the Homestake Laboratory Conversion Project.

Liability would turn out to be a big deal. Under existing Superfund laws, Homestake was responsible for closing and cleaning the mine. However, it was also responsible for any future environmental problems that occurred in connection with the mine, indefinitely. Even if the mine was transferred to scientist or government owners, Homestake would be legally responsible for the insurance policy unless some new legislation changed their Superfund obligations. Thus, the company would be held accountable for anything that happened in the mine despite the fact that they wouldn't be operating, maintaining or monitoring the facility. Superfund laws are meant to protect communities from environmental hit-and-run, when companies damage the environment and then flee cleanup responsibilities. But in this case, the laws meant to protect the community from exploitation also hindered further development of the mine.

Mayor Tom Nelson told me, from his windowless basement office in Lead's art deco city hall, that in the three years since Homestake made the initial offer, "It's been a real rollercoaster." Shortly after Homestake announced closure, a Canadian gold-mining corporation called Barrick bought out the entire Homestake Company. Barrick proceeded to shut down the mine since no transfer plan had been worked out, prompting bubbles of local resentment and a few complaints about the "Canadian Invasion." "A lot of people thought that it was going to be like a turnkey operation," Nelson said. "Homestake left on December 31 [2001] and the scientists would come in on the first of the year." It would turn out to be a lot more complicated.

In 2002, South Dakota senator Tom Daschle made the laboratory his pet project and introduced legislation that gave the state ownership of the lab while the federal government took over the insurance policy. But Congress saw the bill as a "sweetheart deal" and drafted a revised version with more stringent EPA inspections. These would require Barrick to update the infrastructure of the mine on behalf of the scientists. Barrick refused. Some took the ongoing bureaucratic mess as evidence that there was something dangerous in the mine and questioned whether the company was trying to squirm out of its responsibilities to the environment and local community by "donating" the land (and its problems) to the government. But most hoped that something could be worked out: Barrick could retain responsibility for any environmental problems caused by mining, but also donate the mine without being forced to finance the scientists' future projects. Progress was slow.

In 2002, the company announced it would shut off the pumps that kept the groundwater from seeping in and flooding the mine. Two physicists traveled to Lead and picketed at the mine's entrance. Seventeen Nobel laureates sent a petition to Barrick, asking the company to keep the pumps on to preserve a "national treasure, with the potential to become the world's finest underground laboratory." The NSF set aside $10 million to pay for pump operation as the legal issues were worked out; enough to keep the mine "on life support" until 2006. But Barrick balked and refused the money. The city of Lead took legal actions against the company. But in June of 2003, the NUSEL update conveyed the frustrating mixture of good and bad news that was becoming a recurrent theme in this project: "1) Good news: unanimous NSF site panel selection of Homestake 2) Bad news: Barrick committed to flooding." The mine was inspected and cleaned. Although the basic circulatory system of shafts, elevators, electrical wiring, pumps, tracks and cooling system was left intact, everything else was taken out. The pumps were shut off and the water level started to rise last summer.

"So they took it apart, they took the perchlorethylene out. I don't know what else. I don't know what the chamber looks like now. I doubt they tore it out or anything," Gilles said, recalling the laboratory where he worked as a consultant after retiring from Homestake. "Maybe a few pieces of steel were left," said Ken Lande, who ran the laboratory until the end. Each piece had to be taken up the small shaft elevator piecemeal – the same way that the Nobel Prize winning experiment had entered over thirty years earlier.

Homestake's shafts were sealed this winter. It would take at least 20 years for the mine to fill to the brim, according to most estimates. But according to sensors inside the mine, the water is now rising to the 7400 foot level, the depth where scientists proposed building at least one large chamber. As long as the water does not reach the 4850 level, the costs of pumping out the water and rehabilitating the tracks, rock bolting, and electrical systems will still be far less than mining out a new site. But many within the scientific community have turned to other regions of the country, fed up with the slow pace of bureaucratic negotiations and concerned about the flooding. Within Lead, people have resigned themselves to an interminable wait. "Godot Schmodot. The Homestake lab beats that record in a walk," Bill Harlan griped in *The Rapid City Journal*. Gilles considers the project from the perspective of a former chief mining engineer and thinks the rock at Homestake is a good candidate for the extensive caverning the scientists require. But like everyone else, he is wary: "Like I say, it's been hanging fire for so long that I…I got to see this yet."

Meanwhile, 360 miles of drifts which once boomed with activity have become a subterranean ghost town. The city above is gradually emptying out and some might say, wilting, like an uprooted plant in unfamiliar soil. From the outside, the mine complex looks like a ghost town. Many of the buildings are boarded up, their doors plastered with signs warning of asbestos and PCB inside.

The control room of the Yates shaft was, at first glance, just what I expected. Here, two giant reels of cable once spun almost continuously, cued by a bell system that told operators to lift or lower the "cage" (an elephant-sized elevator with open sides) to various levels of the mine. An elevated cockpit furnished with levers, pedals and joystick handles still faces the reel, where a primitive looking pointer and wheel of fortune helped the operator steer the cage to different levels. Now, nothing in the room moves. Greg King, who worked for Homestake for 30 years and now manages the water reclamation project with Barrick, drove me up here. He unlocked the echoing, empty building and let me poke around. Just as I was beginning to feel certain that the enormous machinery represented nothing more than a magnificent monument to mining, he explained the unusual care the miners took during their last days of work. They polished and repainted their individual machines, as if this were not truly the end of the mine. A man named Don Garrett left his helmet, spray-painted gold, near one of the massive reels along with a piece of paper proclaiming that Don Garrett last ran this hoist in June 2003. He painted the massive machinery a bland, clean gray before he left, "to keep it looking pretty for the future," King said. That kind of devotion is atypical, he said, for men who know their jobs will soon end. The parts of the mine that could be used for the lab have, it seems, been preserved rather than shut down.

In the shaft room, where the miners would have piled into the cage to go down for their shifts, the gateways underground have been sealed with a hard, white foam. It is waterproof and airtight, which prevents ice from forming and falling into the mine. King pointed out that the foam cover, which looked to me like a permanently sealed porthole, would preserve the timber and the machines still underground. If the South Dakota legislature were able to work out a deal with Barrick to transfer the mine and also get NSF approval, the shafts could be reopened and work could start immediately. King himself has invested time in the lab efforts. He has given scientists tours of the property and held the cue cards for the Homestake Conversion Project video, which was presented to the legislature a few weeks after my visit.

King's upbeat, active outlook seems to be part of an attitude shift in the region – from nostalgia to action. Lead is a resilient city. Its main street has been relocated several times after destructive fires and land sinkage. But it isn't a western town with a history of community initiative. "Lead was and is, by its history, a mining town, a company town," Mayor Nelson said. "They built the houses for the employees, they built the huge department store downtown that was for the employees. You went in on one floor and got your paycheck and had your charge account on the next. They kept you in town." Homestake provided jobs, free housing, a high school, the first kindergarten west of the Mississippi, a police force, hydroelectric power, sewage systems and free health care. Below the 1,000-seat opera house in the center of town, there was a bowling alley, and an indoor swimming pool. Everything was provided by the mine. Historian Joseph Cash wrote about the unusually friendly paternalistic relationship between town and company in *Working the Homestake.* "Almost all agree that physically the worker was very well cared for…The *Engineering and Mining Journal* spoke glowingly of the physical conditions in Lead but said that in regard to the worker, 'the only condition is that he shall have nothing to say about it himself.'" Like an overbearing parent, Homestake did not prepare Lead to be pushed out into the world on its own.

On a tour of the Episcopal Church on Main Street, I walked down a narrow staircase to the basement chapel where children attended Sunday school. My guides marveled at the design of the children's pews – benches that folded into flat wooden boards, with little collapsible kneelers to accompany them. "Aren't those clever? Who thought of that, I wonder?" Al Gilles asked his neighbors. "Homestake, probably," Ivo Murdy joked, half-seriously.

Even two years after closure, the mine is at the heart of Lead. Many people check gold prices each morning, out of habit. The massive Yates and Ross Shafts jut out of the hillside, visible from most places in town. The few restaurants are filled with pictures of mining, even though far few miners now sit at the tables. The Golden Hills Hotel, the Gold Town Motel, the Black Hills Mining Museum and the Stampmill restaurant line Main Street along with old mine cars, bits of old machines, and a giant plaque over a mock-up of a mine entrance that explains "What Mining Means to Americans." Even a computer store bears mining's imprint – a miner crouches next to the leg of his drill and aims the carbide bit toward the side of the building above the sign for "Dyse Pro Computers." As you walk down Main Street toward the mining operations, a huge

1,000-foot deep terraced depression called the Open Cut yawns open on the left, shielded by fencing. Mining's mark is indelible.

Dan Cornejo, the city planner who is working on a comprehensive plan to guide Lead's business development and urban planning over the next 20 years echoes Mayor Nelson: Lead's biggest challenge is motivating change. "It's not a community of managers that is used to making plans, assigning responsibility to themselves and others," he said by phone. But Cornejo notes subtle differences between Lead and another of his jobs – an old coal mining town in Nova Scotia where the prevailing attitude was, "Nothing good will ever happen for us again." In spite of the sorry look of the empty storefronts and dilapidated houses, you can feel the strange throb of enthusiasm in this town.

"I tell you what, they're fairly resilient, there's a lot of up-beatness out here," Mayor Nelson said, sounding almost surprised by his statement. High school students have told Cornejo that they would like to live in Lead as adults, if there are jobs. Jackie Fuller, the former mayor, is certain that Lead will be discovered. "My kids come home and they roll down the windows, whether it's winter or summer because the air is different up here, it's cleaner and fresher. They love the pine smell." Fuller currently heads a project to rebuild the opera house, which was gutted by a fire in the 1980s. The numbers reveal the extent of Fuller's unwavering optimism: it's a $3 million project to restore a 1,000-seat opera house in a town with just 3,027 residents. But Fuller truly loves this area and believes, without reservations, that this area of the country will thrive with or without the help of the lab. Lillian Hall of nearby Spearfish repeated Fuller's enthusiasm in poetry: "I came from eastern South Dakota and the skies are bluer and the clouds are whiter and the trees are darker out here."

But as any visitor to Lead will notice driving up the hill to Main Street, Lead welcomes the lab. A colorful mural painted by schoolchildren depicts "Our Mining Past" and "Our Science Future." On one side of the mural, miners with hard hats work in timbered underground tunnels. Above them, a Homestake sign is embedded into the hillside like the "Hollywood" sign in Los Angeles. On the other side of the mural, an atomic symbol hovers over the forested hills. Smiling scientists in lab coats work underground with the artist's rendition of their equipment: big tanks and conical, igloo-like accoutrements of science. "National Underground Laboratory," the mural cheerfully concludes. Above the mural, Pizza LAB, one of the few lunch places in town, anticipates the shift as well. Intermittent cars are adorned with bumper stickers printed up by the local newspaper, announcing "I ♥ neutrinos!"

At the heart of this populist laboratory movement is Dick Gowen, a spry man who buzzes with energy. Gowen works out of the Homestake Lab Conversion Project offices in downtown Rapid City, right next to western South Dakota's only "skyscraper," a towering 11-story building. With a staff of two, an abundant supply of gold-colored "Homestake Laboratory Conversion Project" pins in a basket, and a toy truck bearing a decal exclaiming "South Dakota Science on the Move," Gowen is surrounded by propaganda and hope. He retired as president of the South Dakota School of Mines and Technology on midnight of May 31, 2003 and was summarily appointed the head of the Conversion Project on June 1, 2003 by Governor Mike Rounds. At that time, the project seemed near dead. The pumps were being shut off and Daschle's legislation had failed.

People in Lead were peeling the neutrino bumper stickers off their cars and throwing them away. But Gowen has turned the situation around. "I'm a project-oriented type person," he told me proudly. "Go do it. Let's get it done. So that's what I'm doing."

For the past year, Gowen has been bargaining with Barrick, commissioning the design of a core laboratory facility, and writing legislation proposing that South Dakota own the mine and the insurance policy. Gowen and his team used information from the mine's closure inspections to assess the risks involved with the laboratory. They decided the lab – not just a lab, but what Gowen calls "the premiere underground laboratory in the world" – was worth a sizeable wager.

So Gowen drafted audacious legislation, proposing that the state set aside $24.5 million in order to buy an insurance plan, take over liability, and create a South Dakota Science and Technology Authority to manage the facility. In the weeks after I met with him, the legislation passed by a nearly unanimous vote; the two dissenters were Native Americans who supported the lab, but protested the taking of the land from their people over a century ago. In the weeks since, Gowen's office (now the Science Authority) submitted their report to the NSF, including a design for the lab and a science proposal authored by Marvin Marshak. If the NSF accepts the proposal, the Science Authority will act as landlord, building the basic facility and renting the space out by 2009.

Scientists have been calling for an underground lab since 1983; no one would be surprised if underground science was stalled again. But even if nothing happens, the Homestake effort has engaged regular people as allies of science. The innovative legislation circumvented a stalemated political, scientific and legal feud that had gone on so long that few believed it would ever change – and transformed the scientific question into a democratic issue that required exchange between scientists and citizens. Gowen's initiative has inspired many people (including scientists) who thought the prospect of the lab was long gone.

Scientists themselves dislike entanglements with politics. In the last update to the NUSEL website, organizer Wick Haxton announced a new email discussion list, but added "the email list will be made available to any group wanting to communicate about NUSEL science (no politics!)" Over the last year, Gowen and Governor Rounds have resolved the legal problems and offered to make a huge investment on behalf of the scientists. "Gov. Rounds' initiatives represent an unprecedented commitment by a state government to basic science and technology research through a public policy initiative," Marshak wrote in the Project Description for Homestake. South Dakota has assumed risks that can never be fully predicted, convened the legislature around basic scientific research, and sorted out complex legal issues that have made scientists and civilians extremely impatient over the past three years. "The state effort has been unique that I know of," Lande said. "I don't know of any other state that has gone through quite this much effort to get a science laboratory."

Other national laboratories scattered across the country, such as Brookhaven and Oak Ridge, are owned by the Department of Energy which also finances and controls the design of many of their experiments. The state and the Science Authority will take no such responsibility. If Homestake becomes the National Underground Laboratory, the Science Authority will issue bonds guaranteed by the National Science Foundation. These will be paid back as the NSF rents the space for experiments. The scientists will be responsible for procuring funding for their experiments and the state will manage the site and ensure its safety. Unlike traditional scientific funding schemes, in which taxpayers' money is distributed by committees and officials in the NSF, this scientific discussion has directly engaged the public who funded it.

That public got its first formal exposure to the proposed science experiments from Marshak and colleagues on "Homestake Day at the Legislature" a few weeks after my visit with Gowen. The general idea was already well understood after three years of anticipation: Physicists, instead of miners, would pass ant-like through the mine, making measurements. Mayor Nelson described the activity of "the whitecoats" (his name for the scientists) as following: "Neutrinos, geology, geomicrobiology, you know, beta decay, all those terms that I'm not really familiar with." But South Dakotans got a wallop of science at Homestake Day.

The scientists started out slow. "We are the nerds you knew in high school. We like football too," Marvin Marshak joked to a receptive audience before plunging into the material. "But dark matter and things like that actually turn us on even more."

The scientists introduced their experiments to the audience as accessibly as possible, with varying degrees of success. But an interesting thread wove together the otherwise unconnected lectures about specific projects. The National Underground Laboratory that the scientists told South Dakotans about would be a different kind of facility. Right now, underground scientists fly to Japan or Canada for a week at a time to tweak the apparatus, collect some data, or briefly meet with their many collaborators. Homestake would be designed not as that sort of "come and go" facility, but as a subterranean university in which researchers were encouraged to stay, teach, and mingle. Contact between scientists measuring dark matter, ascertaining whether the proton is eternal, examining "extremophile" subsurface life, or developing sensitive radiation detection techniques could create fertile ground for the cross-pollination of ideas. Physicist Harry Miley lauded the interdisciplinary laboratory design. "Instead of having a 20-year process of getting technology and information out of the pure science into the field, we need to short circuit that," he said. For Lead, such a lab would be a boon to the economy and to students. A research facility that functions like a home to science rather than a fast-food drive-in could change the character of the state.

In western South Dakota, universities lack degree-granting programs in physics. Two "Science on the Move" tractor-trailers drive between small towns, giving under-equipped grade schools a mobile laboratory for physics, biology and chemistry experiments. Students with a serious interest in science must leave to pursue their educations and careers. One such student, Ernest Lawrence, (of Lawrence-Berkeley National Laboratory) moved to California in order to invent the cyclotron. The universe of concern for the local government, and even for some of the scientists, is not limited to outer space or subsurface life: "The bigger issue is the multi-state area of the Midwest. It's the 'have-not' states," Gowen said cheerfully.

Even with the option of going elsewhere, there isn't strong interest in research science. Dan Durben, a chemist who teaches physics at Black Hills State University, complains that students don't consider science careers or even science classes because there are no jobs or local role models. Durben interrupted his account of the many obstacles to teaching science with a single positive example of interest in his classes. "I teach an intro level astronomy class and we'll spend, oh, maybe half a class talking about what was going on down there because it's in their backyard," he said. The neutrino experiment is "the one part of a test, every semester, when I ask them questions about that, they do exceptionally well." A national lab at Homestake could help demystify science, giving young people a local reason to become interested in the much wider world of science: with knowledge of how the sun burns, how the universe began and how it might end. It might also keep scientists and engineers in the state. In the editorial section of a recent issue of *The Rapid City Journal*, a student from the South Dakota School of Mines & Technology wrote, "Converting the Homestake Mine to a research and technology center appears to me to offer hope of reducing the number of college graduates and other young people leaving South Dakota…Most of us from ranches and farms would prefer living near open spaces in South Dakota. The reality is that most Tech students must leave after graduation." Universal science, local scientists.

And yet, the Homestake efforts are extremely, undeniably local. Many families grew up around and within the mine: they, their fathers, grandfathers and great-grandfathers worked in the same tunnels. "It's kind of like losing your life's work for some people," Bob Harlan replied, when asked what losing the mine meant to him and his former co-workers. This local loss is in most people's minds when they discuss the need for the scientific lab. "Save for the NSF" and "A mine is a terrible thing to waste" were among the graffiti etched into the walls of the mine when it closed – alongside graffiti from another time, when miners still used carbide lamps. "[The lamps] would give off soot. So the miners would hold their lamp up to the wall and write their names and dates on the wall," Harlan said, describing vestiges of a time when horses still tugged around the cars in the mine. The dream of a scientific future in Lead is inextricably intertwined with the history of the mine. In 2003, scientists declared Homestake the number one site for an underground laboratory based on technical merit. Ex-miners and citizens judge the project based on different, but in some ways very compelling standards: The mine is a historical and scientific artifact that should be used if it truly is, as the scientists have determined, the best site.

Lande understands and respects their deep emotional ties, having lived in the area. "There's generation after generation of the same families working and building this mine. They consider it theirs, and – it is. They built it with their hands, their sweat and their blood. And its future is their future. They take a proprietary sense." In a way, this kind of devotion is inspiring for the scientists. "This is a wonderful background for us," Lande said by phone. "The next generation of scientists [from South Dakota] will feel equally supportive and interested in and devoted to this experiment."

People who look to the lab as a miraculous economic cure-all will, inevitably, be disappointed – whether or not it is built. Throughout the question and answer period on Homestake Day, concerned legislators and businessmen asked about economic effects and jobs. Could side effects of the lab be similar to the booming technology alleyways that transformed other sites around the country – "the Oak Ridge effect"? Physicist Kevin Lesko's answer was matter-of-fact. "I build experiments. If in the process of building experiments I find a way to better support the underground, I didn't do that." Realists in Lead are quick to point out that even if they get the lab, many scientists will choose to live in Spearfish, the college town to the north, or in Rapid City, with its stores and cultural attractions. The lab will never fill the employment gap that the mine left behind. But the planning commissions and town meetings that have been organized to help prepare for the lab have also exposed opportunities that exist within the town itself. There's no place to get a cup of coffee in Lead. There are no outdoors outfitters to equip people for the skiing, hiking, snowmobiling, mountain-biking and fishing that attract people to the Black Hills. There are plenty of opportunities to build the local community while Lead waits for the NSF to make its decision.

Jackie Fuller told me that she discusses the lab everywhere – when she runs into friends lifting weights at the YMCA, on the way to Rapid City to see a musical with family friends. In the post office in Rapid City, the postal clerk discussed Homestake with a customer while I waited to buy stamps. "It's happening right now," said the customer. "Well, it's certainly worth waiting for," replied the clerk in a knowing tone. Nearly every single day this January, a story about neutrinos, the lab, the legislative negotiations, or physics landed on the front page, above the fold of *The Rapid City Journal*. Neutrinos have also penetrated the best-seller list: *The Zero Game*, a murder mystery by Brad Meltzer, follows its characters into the "Homestead" mine in a North Dakotan town called "Leed," where a physics laboratory is a cover operation for the production of nuclear weapons. Another best-seller, physicist Brian Greene's *Fabric of the Cosmos* prominently features neutrinos. In this swirl of popular attention, the NSF will decide whether to turn the pumps back on or to allow the neutrinos to slowly drain out of consciousness as the mine floods.

On February 23, Lead celebrated its 4th Annual Neutrino Day. Dr. Gowen, Mayor Nelson, the Lawrence County Commissioner, "Miss Neutrino," and Oppie the Underground Lab dog were in attendance as well as more than 100 people from the area. Enthusiastic newspaper reports described Miss Neutrino decked out in a visor, an iridescent, patriotic outfit studded with sequins and a cape covered with smiling neutrinos. No one needs to "save" Lead, South Dakota – not Miss Neutrino, and not the lab. Like other small, determined towns in beautiful places with historic spaces nearby, it will continue to weather the seasons. But science could transform the city, the state, the Northern Plains, scientists, and our vision of the universe. They're all intertwined.

"Lead," Dick Gowen is fond of saying, "is the neutrino capital of the world." As this experiment between policy and science plays out it will be interesting to see whether, like a neutrino, Lead can change flavors. It could disappear off the map like the missing neutrinos in Davis' experiment. But it seems more likely that this quirky, mile-high city could become something new, something we haven't seen in science or in the world, and couldn't have fully anticipated.

A Note on the Research

It is difficult for me to tell when, exactly, this project started. During my sophomore year of college, Larry Hunter introduced me to the quirky particle called the neutrino. I heard an NPR interview in which Ray Davis described his unusual work habits: traveling to an office a mile underground to do work that even the scientific community thought to be rather outlandish. I thought that it had the makings of a great story, but I was a physicist not a storyteller and I kept my mouth shut and took notes on the particle.

I later realized that the Homestake Mine in which Davis carried out his experiment was the same one that I had visited on family trips. Lead was the town where my grandmother had lived most of her adolescent life, since her father served as general manager during the Depression. The family history which motivated a trip to Lead, Deadwood, Rapid City and Spearfish had caused great embarrassment at the time since I found it exceptionally hard to justify it to my east-coast friends. "Why would you ever go to western South Dakota for vacation?" they'd ask, incredulously. But the town turned out to be the center for something surprisingly sophisticated – a physics discovery that really caught my attention.

I was doing summer research at the University of Washington's physics department just as the exciting neutrino results were emerging from the Sudbury Neutrino Observatory (SNO) collaboration, in June 2001. Much of the SNO group was based at UW and I heard many exciting lectures by physicists who were releasing their first, exciting bits of data. Later, Wick Haxton gave a presentation on a little-known gold mining town out in the middle of nowhere that was currently the best shot for a new underground laboratory in the U.S. Homestake resurfaced in my life.

The research that produced this work originated from an odd mix of scientific, historical and personal interests. I read many, countless articles from the archives of local papers like *The Rapid City Journal*, *The Black Hills Pioneer*, and *The Aberdeen News*. I slunk around the Phoebe Apperson-Heart library in Lead, searching for old receipts and correspondence in the archives section and perusing the in-house mining publication, *Sharp Bits*, which occasionally came out with feature issues on the neutrino experiment. I watched the videos made for mining visitors and videos made to persuade scientists and people to support the laboratory project. I attended physics colloquiums about the latest research in neutrinos and drew on the expertise of graduate students and the principle investigators of the neutrino problem in order to stay informed about what was going on in neutrino science.

I also read, as the disorderly chaos of papers, books and article clippings around my room suggests. I read technical articles from physics journals, popular accounts of the solar neutrino problem, proposed legislation, proposed NSF grants and books about everything from the sociology of neutrino detection to the history of our understanding of the sun. I was fortunate that a burst of activity was occurring as I was writing my thesis: I have been following the news as closely as possible.

The Kelly-Douglas fund generously sponsored the visit to South Dakota from January 8 – January 15, 2004. That trip crystallized my story and provided the characters, plot and scenery. Fitting the whole story together was another matter. Thanks to Rob Kanigel for nudging me along.

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