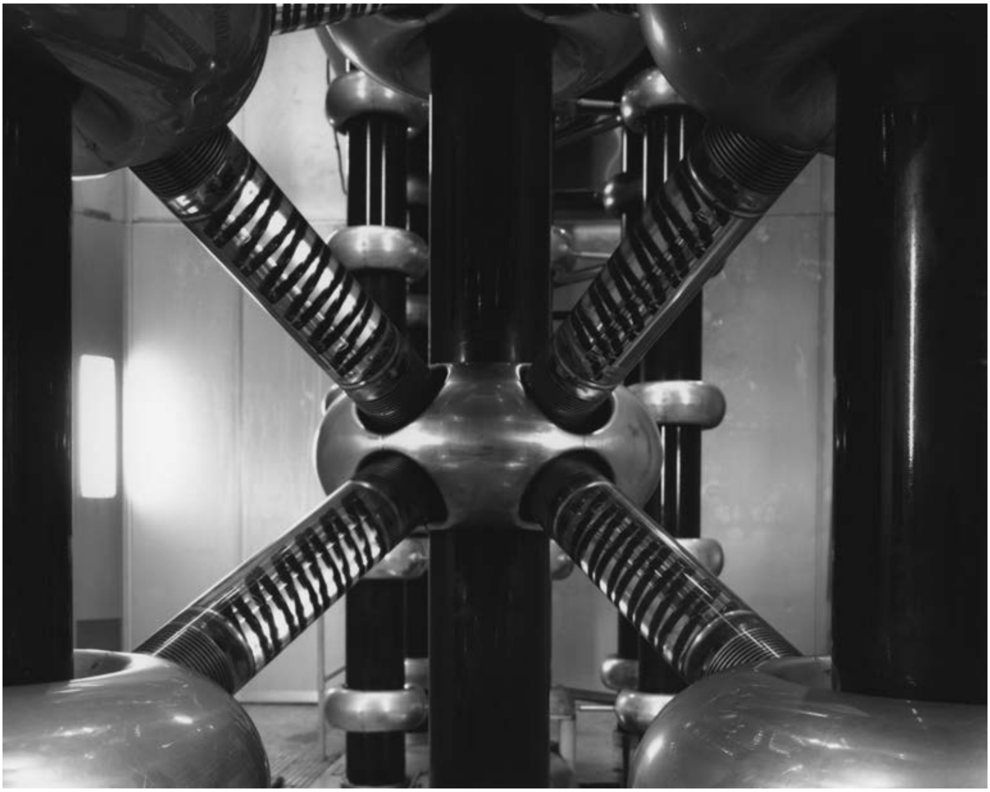


BACKSTORIES:

The Physics Experiments Behind *Stanley Greenberg's* "**Time Machines**"

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JANET **CONRAD**

Janet Conrad, a professor of physics at MIT, leads a research group devoted to exploring the nature of the tiny, almost massless neutrino, which is sometimes called the "ghost particle."

Janet received her Bachelor of Science degree from Swarthmore College, her master's from Oxford University, and then, in 1993, her Ph.D. from Harvard. Before moving to a professorship at MIT, she was previously a postdoc, and then professor at Columbia University in New York.

In addition to teaching at MIT, Janet is also involved in the previous MiniBooNE experiment and future MicroBooNE experiment located at Fermilab, as well as Double Chooz, which is based in France. She is also co-spokesperson of the proposed IsoDAR and DAEdALUS experiments.

STANLEY **GREENBERG**

Stanley Greenberg has photographed the hidden infrastructure of New York, contemporary architecture under construction, and physics and astronomy installations around the world. He received a Guggenheim Fellowship in 2005. The physics project was supported by a grant from the Alfred P. Sloan Foundation. Greenberg has also received grants from the New York State Council on the Arts, the New York Foundation for the Arts, and the Graham Foundation, among others.

His work has appeared in multiple exhibitions, most recently at the Art Institute of Chicago in 2010, and previously at the Metropolitan Museum of Art and the Whitney Museum of American Art. In addition to "Time Machines" (Hirmer Publishers, 2011), Stanley has also published "Architecture Under Construction" (University of Chicago Press, 2010), "Waterworks" (Princeton Architectural Press, 2003), and "Invisible New York" (The John Hopkins University Press, 1998). He lives in Brooklyn, New York.

Introduction

When Stanley Greenberg first wanted to photograph Professor Janet Conrad's laboratory, he thought he was just coming across town, from Brooklyn to Columbia University. But when she told him it was really 800 miles, to Fermi National Accelerator Laboratory, Illinois, he nonetheless willingly agreed: "Stanley is game for anything," Janet says, "that will bring him a compelling photograph." Consequently, to produce "Time Machines," he has traveled across six continents and seen nearly every major particle physics laboratory.

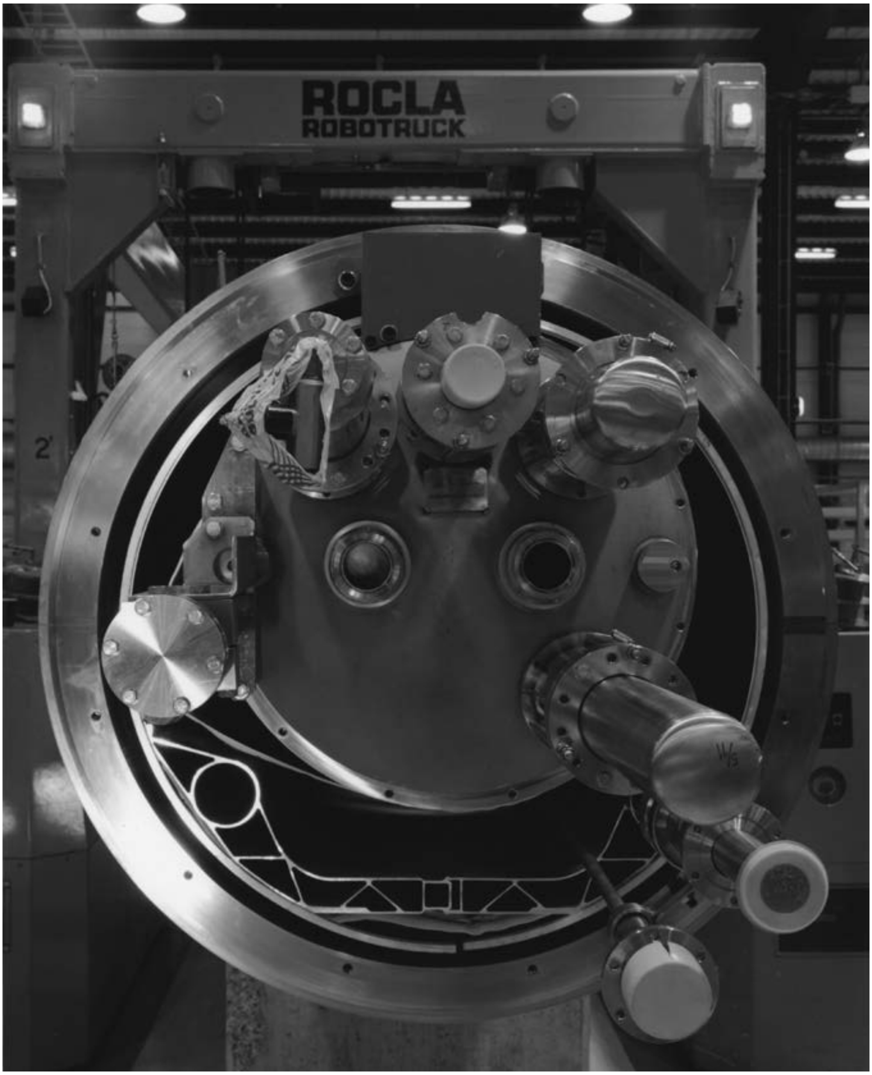
Despite these distances, it is a small world. Laura Gladstone, Janet's student who had showed Stanley around Fermilab before joining the IceCube experiment, met him again in Antarctica! Similarly, although over a smaller distance, when Janet moved from Columbia University to MIT, she did not expect to run into Stanley again. So she was delighted to discover he was presenting this MIT museum exhibit.

The photographs in this exhibit show the apparatus of particle physics experiments as stunning and intriguing images. For physicists, juggling many different experiments and projects, with all the daily stresses that entails, it is easy to be too busy to remember the truly wondrous aims of this work: to further understanding of the nature of the universe. Stanley's photographs, which, Janet says, "capture the beauty of the very instruments used for this purpose," are a wonderful reminder of this great goal.

It seemed, therefore, that Stanley's exhibition was the perfect project for the science writing class Janet teaches at MIT. Each student chose a photograph from "Time Machines" that they found inspiring, investigated the "backstory" of the experiment behind the photograph, and wrote an accompanying essay. This booklet contains five of these stories. We hope these take you even further into the photographs you see today.

Kate Phillips

Dipole magnet, Large Hadron Collider, CERN, Switzerland, 2006



Kate graduated with a Bachelor of Science degree from MIT in 2012, majoring in biology and physics. After graduating, she worked at the Harvard School of Public Health researching HIV. She is now a medical student at the University of Michigan and lives with her husband, Jon, and their cats, Batman and Ironman.

The universe is chock-full of matter. The earth, your cat, and everything we can see are made of matter. Antimatter, matter's dark twin, is conspicuously absent from the universe, appearing only in high-energy collisions and cosmic rays. This is all well and good, because if antimatter were as abundant as matter, we would all be annihilated into bursts of light, but the crazy thing is that no one can explain why the antimatter is so scarce. In the Big Bang, matter and antimatter were theoretically produced together in equal amounts. So where did all the antimatter go?

The Standard Model of physics, which is the current theory describing all of physics, rests on symmetries. If you drop a watermelon at 3 p.m. or at 7 p.m., the laws of physics governing the movement of the fruit will stay the same, so it will make the same "splat" at either time. This is known as time invariance, or symmetry of the laws of physics through time. In the same way, the Standard Model requires charge-parity (CP) symmetry, which says that if you switch the charge of a particle (positive to negative) and the handedness of the system (right- to left-handed), the new particle in the new system should be indistinguishable in behavior from the old. CP symmetry therefore implies that a particle and its antiparticle should behave in similar ways, since they are identical in mass and differ only in charge. Therefore, if physicists can find instances where CP symmetry is violated, they may be able to explain how matter became so much more prevalent than antimatter in the universe during the early instants of the Big Bang. The Large Hadron Collider Beauty (LHC-b) experiment is looking to do just that.

The LHC-b experiment at CERN's particle accelerator studies the behavior of big, heavy particles like B and D mesons in the hopes of seeing interesting physics, including CP symmetry violations. In order to study these particles, the massive LHC-b detector has layers and layers of sensors to collect all the information possible on the particles passing through. Magnetic fields bend the particles so you can see which charge they are; silicon wafers can actually track the path of charged particles; and charged particles leave detectable cones of blue light in a path behind them. Finally, particles hit the calorimeter, a huge wall of metal and plastic sheets sandwiched together, and lose their energy in a burst of UV light that photomultipliers capture. The calorimeter is especially important in detecting neutral particles, which don't make light cones or interact with the magnetic field or silicon wafers. In fact, neutral particles are invisible to this complex detector until they collide with the calorimeter. From calorimeter data, physicists can reconstruct the energies of incident particles. Although the LHC-b experiment studies mostly B and D mesons, the detector only sees smaller particles made in the decay of these big mesons; scientists use data from these decay products to piece together the behavior of the mesons.

The LHC-b collaboration has recently found some clues to the puzzle of CP symmetry and the origin of the universe, and their data has the particle physics community buzzing. They detected CP symmetry breaking in the decay of strange B mesons (particles made of a bottom antiquark and a strange quark). What does that mean? In one of the most bizarre phenomena in physics, this neutral heavy particle called the "strange B meson" (B_0^s) changes into its antiparticle (the anti-B_0^s) and back a thousand billion times in a single second. During this time, while the meson is either itself or its antiparticle, it can decay. The particles produced during this decay, which are the ones that hit the LHC-b detector, differ depending on whether the particle or its antiparticle decayed. The LHC-b has found that the strange mesons and antimesons decay at different rates, and this is the CP symmetry violation they have been searching for. While this result may sound modest, it is groundbreaking because the particles aren't behaving the way the Standard Model says they should. With much more data, results such as these could be used to validate a new model of physics. Dr. Marina Artuso, who has been working within the LHC-b collaboration since 2005, described the discovery of these symmetry-violating decays as "the first glimpse of perhaps new physics beyond the Standard Model." Some new physics theories have already been developed to explain the gaps in the Standard Model. The theory of supersymmetry adds lots of extra symmetries to the Standard Model in order to explain things like CP symmetry violation, which oddly goes away when you impose more restrictions on the system. Many theoretical physicists devoutly support supersymmetry as the new theory of everything. The only problem is that other new data coming out of the LHC-b squeezes the parameters of supersymmetry to the point where it looks like it isn't a viable theory anymore. So whatever new physics is causing the CP violation found in strange B meson decays, it doesn't look like supersymmetry can explain it. The more the LHC-b experimented to see if particles followed the rules of supersymmetry or of the Standard Model more closely, the more convincing the Standard Model looked: "My God," Artuso said, "the Standard Model seems to be better than we even thought it was." These new results have not gone over well with supersymmetry devotees; they seek out Artuso and her colleagues to defend their beloved theory. With supersymmetry falling out of favor, the quest for novel physics to explain life, the universe, and everything is on, with experimental data from the LHC-b pointing the way.

You couldn't tell from its recent successes, but the LHC-b has had its share of disappointments. In September 2008, days after the LHC had sent its first test beam through the accelerator, a magnet got a little bit too hot, and the system got out of control: explosions ripped through the accelerator and destroyed sections of it. The repairs took months.

To physicists like Artuso, who had been looking forward to the start of the LHC for years, the accident was a huge disappointment. "So much in the future of high-energy physics rests upon the shoulders of CERN," she said, and after all the hype that had been built up around the start-up of the LHC, the accident was "catastrophic." But the LHC-b collaboration didn't sit idly while the newly built LHC was undergoing extensive repairs: instead, they spent the time refining their software, adding in extra calibration and monitoring abilities. Artuso points out that although the accident was a setback, the delay time was "put to good use." The flurry of new data coming out of the LHC-b in the past month is a testament to the resilience of the collaboration in overcoming these difficulties.

LHC-b researchers are well aware that much more research is necessary in order to build upon their recent results. While the current CP violation data is novel and exciting, it isn't enough for theorists to grab hold of and try to build a viable model around it. One next step for the LHC-b, Artuso said, is to make the measurement of the asymmetry more precise. Right now, the asymmetry is measured as a difference between the B meson and its antiparticle, but if each value could be measured independently and accurately, that would yield even more information for theorists to use. The LHC-b is also looking for new types of CP violation, including in the behavior of the tiny neutral particles called neutrinos. With more results on CP violation, the LHC-b hopes to provide an experimental foundation for explanations of how antimatter disappeared as matter formed the universe. The recent LHC-b results, Artuso says, are "the first chapter of a long story. But it is very exciting."

Gregory Lau

Clean room, LIGO, Louisiana, 2008

Gregory graduated with a Bachelor of Science degree in physics and economics (2012) and a master's in finance from MIT (2013). Upon graduation, he was drafted into the Singapore Navy and will pursue a career in policy making in the Singapore Government after his military stint. Gregory has many fond memories of MIT: he will never forget his many hours admiring Bose-Einstein condensates dancing in laser light in the middle of the night and his many attempts at shooting clay pigeons projected at random trajectories—to name just two.

Imagine detectors able to sense change in length as small as a thousandth of the diameter of a proton. Such sensitive detectors are required for experiments to verify Einstein's seminal general theory of relativity. Think they cannot exist? They are already found in one of mankind's most ambitious scientific experiments, the Laser Interferometer Gravitational Wave Detector (LIGO).

The largest project funded by the National Science Foundation, LIGO is an attempt to directly measure gravitational waves, which are key predictions of the general theory of relativity. General relativity predicts that as large masses such as stars move rapidly, ripples in space-time, similar to water waves, will be produced and propagated across galaxies. Thus far, these waves have only been indirectly measured through observations of binary pulsars (rapidly spinning remnants of exploded stars) by Hulse and Taylor (Nobel Prize 1993). LIGO aims to bridge the gap between theory and experiment by directly detecting gravitational waves through high-precision laser interferometry.

The experiment consists of two observatories, one in Washington and one in Louisiana. These L-shaped observatories have perpendicular arms measuring 4 kilometers. Laser light is emitted at the intersection of these arms and sent through both arms to mirrors, which eventually reflect the light in both paths back to the intersection. Gravitational waves that travel through the observatories will perturb the lengths of the two arms, causing laser light from the two sides to travel different distances and thus become out of phase. Such phase differences can then be detected with a photodetector located at the intersection of the two paths where both beams of light interfere with each other. To rule out spurious detections, measurements of gravitational waves from one observatory will need to corroborate measurements at the other for conclusive evidence of gravitational waves.

Essentially, LIGO is a scaled-up interferometer, similar to the interferometer used in the famed Michelson-Morley experiment which disproved the existence of ether and paved the way to special relativity. However, LIGO is faced with a seemingly insurmountable challenge: gravitational waves are so weak that to detect them, LIGO has to be sensitive to changes on the scale of a thousandth of the diameter of a proton, despite the 4-kilometer arms of the interferometer!

Like most people, Jay Marx, executive director of LIGO from 2006 to 2011, only had one reaction to the proposed idea of LIGO on hearing about it as LIGO's scientific reviewer: "This is crazy."

However, the difficulties in achieving this level of sensitivity did not stop the LIGO scientists. Marx highlights three main technical challenges that scientists had to overcome. First, creating, in Marx's words, "the best mirrors in the world": they are made of a single silica crystal with extremely smooth multilayer coating that reflects 99.999% of incident light. Secondly, creating very powerful and stable lasers: the lasers must have up to 10 watts of power, and the frequency of their output must not fluctuate by more than a factor of one part in a billion of the laser light wavelength. Finally, both observatories must be isolated from ambient vibrations. Therefore elaborate "shock absorbers" are required to shield the observatories from natural motions from the ground, and the entire interferometer setups must be encased in ultra-high-vacuum tubes.

All of these challenges were overcome in 2002, when LIGO conducted its first experimental run. From 2002 to 2007, several successful runs were conducted, and scientists from more than 13 countries analyzed the resulting data (LIGO Scientific Collaboration).[1] No gravitational waves were detected. So was LIGO a failure?

Marx answers with a firm no, and lists some of LIGO's scientific achievements. The absence of gravitational wave signals actually allows scientists to place useful limits on several important astrophysical quantities. For example, analysis from LIGO's data allowed scientists to deduce how aspherical the Crab pulsar is. "Rotating perfect spheres will not emit gravitational radiation, but any kind of aspherical object will," Marx explains. Therefore, limits on the observed strength of emitted gravitational waves from the Crab pulsar will place limits on how aspherical the pulsar is. Thanks to the LIGO experiment, scientists can deduce that the Crab pulsar is nearly a perfect sphere, which helps in further studies on pulsar characteristics (Gache).[2] Another example of LIGO's scientific contribution involves placing limits on how many black hole formations occur within a galaxy, due to collisions between pairs of neutron stars or smaller black holes.

The benefits extend far beyond the field of astrophysics. For example, technology developed at LIGO is actively being transferred to industry and other fields of research. LIGO has developed several patents, including oxide bonding of silicon carbide and laser shaping technology (LIGO, MIT).[3] Oxide bonding techniques can be used in building space-based optical systems such as telescope assemblies,[4] and laser shaping technology can be applied to develop directed laser energy weapons and laser radars.[5] Unpatented technology from LIGO also made it into industry through scientific publication and word of mouth. For example, when taking an aircraft in bad weather, be thankful that LIGO prestabilized laser schemes have been used for detection of flaws in carbon aircraft composite structures.[6]

What is next for LIGO? A big upgrade scheduled to be completed by 2015, resulting in observatories with 10 times the sensitivity of the initial design. Called Advanced LIGO, this new project will be able to peer 10 times deeper into space for gravitational wave sources. Since gravitational waves can be detected in any direction, Advanced LIGO will gain access to a thousand times more gravitational wave sources. "The initial LIGO has maybe about 2% chance … to see something," says Marx. "When Advanced LIGO comes online in 2015, it is almost a sure thing we will observe gravitational waves."

Advanced LIGO will be able to observe gravitational waves to probe deep into space. Unlike conventional observatories which can only observe light-emitting interstellar objects, Advanced LIGO will be able to detect dark objects as well, since all moving bodies emit gravitational waves. Scientists will be able to extract information from the waveforms of detected gravitational waves to make inferences about astronomical objects, such as pairs of black holes that are spiraling into each other. In addition, by collaborating with other gravitational wave observatories throughout the world, Advanced LIGO will be able to pinpoint the location of gravitational wave sources through triangulation. Some of the other observatories include VIRGO in Italy, LISM in Japan, and potentially another LIGO observatory in India to be built in the near future. Once this is achieved, scientists will be able to combine data from all types of observatories (optical, X-ray, radio, gravitational waves, etc.) for a more complete description of astronomy.

Excited by these prospects? Both observatories conduct free tours open to the general public. Interested readers are not alone: According to Marx, about 10,000 people a year attend these tours, and the numbers are growing fast. "LIGO does not even have enough staff to handle all the people anymore!" he exclaimed.

Therefore, hurry down to one of the observatories. Given the scientific impact and technological contributions LIGO has made and will offer in the near future, it is one of the most important experiments in modern physics. These tours are opportunities not to be missed. After all, where else can you visit that is so important and interesting, all for free?

1 LIGO Scientific Collaboration. *http://www.ligo.org/about.php.* n.d. Website. 31 March 2012

2 Gache, G. *http://news.softpedia.com/news/Crab-Nebula-Pulsar-Leaks-Energy-Through-Gravitational-Waves-87171.shtml.* 03 June 2008. Website. 31 March 2012

3 LIGO, MIT. *https://www.advancedligo.mit.edu/tech_overview.html* 9 February 2012. Website. 31 March 2012.

4 LIGO, MIT. *https://www.advancedligo.mit.edu/oxide_bonding.html*

5 LIGO, MIT. *https://www.advancedligo.mit.edu/beam_shaping.html*

6 LIGO, MIT. *https://www.advancedligo.mit.edu/tech_overview.html*

Anna **Merrifield**

OPERA detector, Laboratori Nazionali del Gran Sasso, Italy, 2009

Anna grew up in Honolulu, Hawaii, and completed her Bachelor of Science degree in physics with numerical methods from MIT in 2013. She is currently working towards a PhD in climate science at the Scripps Institution of Oceanography in San Diego. In her time at MIT, she enjoyed playing varsity basketball, participating in MIT's Undergraduate Research Opportunities Program (UROPs), and working on homework problem sets with friends.

This is a story about experimental particle physics. If there were someday to be a tome written about the field in the 21st century, the OPERA neutrinos would be afforded a few pages, possibly even a whole chapter. The trajectory of OPERA's faster-than-light neutrino discovery, from its astonishing announcement to its near conclusive disproof, follows that of a Greek tragedy. Tragedy depicts a downfall of a noble cause, which unfortunately looks to be the case for OPERA's neutrino time-of-flight experiment, while allowing its audience to achieve recognition: in this instance a greater understanding of nature and the scientific process.[1]

Before we get into this story, it's important to keep in mind that the world of science is a messy place. Excitement over a promising peak in the data can be explained away as an artifact of the apparatus or, worse, as human error. Major discoveries in physics can be especially elusive. The tiniest components of matter are very hard for us to probe. The ultimate goal is to come up with a theory that unifies the interactions of everything in the universe. It's a tall order, not for the faint of heart.

As you can probably guess, all-encompassing theories are hard to come by. Certain ideas, usually postulated by Albert Einstein, accurately describe the natural world and take hold as laws. An important physical law, the cornerstone of Einstein's theory of special relativity, is that nothing travels faster than light. Even if you got on a high-speed train and stacked another train, which is going at a high speed relative to the train you're on, on top and so on and so forth, the top of the high-speed train stack will still be going slower than light. This nifty property leads to the fact that light is invariant under Lorentz transformation; no matter where you're standing, high-speed train or otherwise, a beam of light will zip by you at the same speed, about three hundred million meters per second in a vacuum. This postulate has been tested and confirmed in many experiments and explains many phenomena.

When a group of Italian particle physicists announced, in September 2011, that they had found a particle, the neutrino, which went against this tried and true theory, there was an upheaval in the scientific community. If OPERA's claim was true, that neutrinos were indeed superluminal, we would be able to know the *effect* of an event before it had a *cause*. The phenomenon of "breaking causality" had severe ramifications to our basic understanding of the forward flow of time.

The OPERA experiment knew the magnitude of its claim and did what any noble group of scientists would do when faced with a “law-breaking” result: open the case up for questioning and public scrutiny. The premise of the measurement was fairly straightforward; it boiled down to measuring the time of flight of a neutrino and the distance it traveled, and dividing the two to get the speed. The neutrinos were created by accelerated proton collision at CERN in Switzerland and detected (no small feat as the mysterious little particle is often affectionately called “the ghost particle”) in an emulsion cloud chamber at Gran Sasso in Italy.[2] Identical Swiss-grade timing systems, receiving information from a mutual GPS satellite, were used to determine neutrino creation and detection times. Skilled Italian surveyors used a combination of conventional mapping and GPS coordinates to determine the neutrino flight distance, even taking into account the slight curvature of the earth over the 730 km beam line. Finally, with all the pieces in place, researchers found the neutrinos made the journey down the CNGS (CERN to Gran Sasso) particle beam quite quickly; if there had been a pulse of laser light zipping down the beam line as well, the neutrino would have beat it by 60.3 ns.[3]

There are a couple of things to consider about 60.3 ns; though the time difference may seem miniscule, being about five million times faster than the average qualitative speed assessment “in the blink of an eye,” it is actually, according to neutrino expert André de Gouvêa, a significant effect. Further, from a statistical standpoint, the number comes from a distribution of 15,223 neutrino events and holds a 6σ significance, meaning that OPERA physicists were 99.99998% sure that they obtained a real result rather than an artifact of the measurement.[4]

De Gouvêa, an associate professor at Northwestern’s Department of Physics and Astronomy, specializes in answering the “questions raised by the experimental neutrino data.”[5] He shared the skepticism of the particle community at large when OPERA’s results were made public. “As a big effect, we should have seen this before,” he said. “So we first had to ask ourselves why is [the OPERA claim] wrong?” Though it may seem harsh, de Gouvêa is simply pointing out the OPERA neutrinos are not the first neutrinos on the block. Back in February of 1987, a large supernova, SN 1987a, showered three different atmospheric detectors with neutrinos, which got to earth about three hours before light. This exceedance is due to the fact neutrinos are the first particles out of the gate in a stellar explosion. If neutrinos actually traveled at the speeds measured by OPERA, head start or not, they would have beat light to earth by *four years*. An exceedance of that magnitude is definitely an effect de Gouvêa and company would have been well versed in prior to the CERN neutrinos.

While the physics community haggled over whether the difference in neutrino energy (low for the atmospheric, extremely high for the OPERA experiment) mattered, the OPERA experiment went back to work improving the result, now 99.99999994% sure of a 57.8 ns exceedance.

The downfall was soon to come. In February 2012, five months after the announcement, sources familiar to the experiment indicated to *ScienceInsider*, a popular science policy blog, that an experimental error was likely the source of the measured difference in flight time. Within the intricate setup, an 8.3 km long fiber-optic cable, connecting the external GPS signal to OPERA's underground master clock, was found to be loose.[6] Upon tightening, the supposed transmission delay of 40996 ns was revised to be about 60 ns longer, which would have increased a neutrino's trip time by 60 ns. Though just one of the statistical errors identified by the OPERA camp, this effect is especially suspect due to the fact it is the same size as the discrepancy.[7]

Less than a month after the first refutation, the ICARUS experiment may have laid the superluminal mystery to rest by finding seven slower-than-light neutrinos in the same CNGS beam. CERN research director Sergio Bertolucci feels comfortable crediting "an artefact of the measurement,"[8] but acknowledges that further rigorous checks are required to topple the over-15,000-neutrino-strong measurement. De Gouvêa remains wary of the accuracy of the ICARUS' +0.3 ns[9] time-of-flight shift. Again, this calls for further tests, but with its new, supposedly more accurate, liquid argon time projection detector, ICARUS should have no problem coming up with a conclusive answer when new neutrinos arrive from CERN in May.

This saga is coming to a close. Fundamental principles of physics remain safe for now, causality is intact, and light regains its throne as the fastest phenomenon around. As OPERA's superluminal claim sinks deeper into the irreproducible sea, the irony of the situation could not have been written more perfectly. It was OPERA who flew too close to Albert Einstein's theoretical sun and was cast down. ICARUS appears to be absolved of its prior mythical hubris and is poised to take flight (relativistically, of course) as the next chapter of experimental particle physics begins.

[1] "Tragedy: the Basics." Classics 201 B: Winter 2004. 3 Mar. 2012. *http://faculty.gvsu.edu/websterm/Tragedy.htm*

[2] "About OPERA: Oscillation Project with Emulsion-tRacking Apparatus." OPERA. 19 Feb. 2012 *http://operaweb.lngs.infn.it/*

[3] Adam et al. "Measurement of the neutrino velocity with the OPERA detector in the CNGS beam." Journal of High Energy Physics. 22 September 2011. *http://arxiv.org/pdf/1109.4897v2.pdf*

[4] Adam et al. 2011

[5] "André de Gouvêa." Department of Physics & Astronomy, Northwestern University. *http://www.physics.northwestern.edu/people/personalpages/adegouvea.html*

[6] Fig. 6, Adam et al. 2011

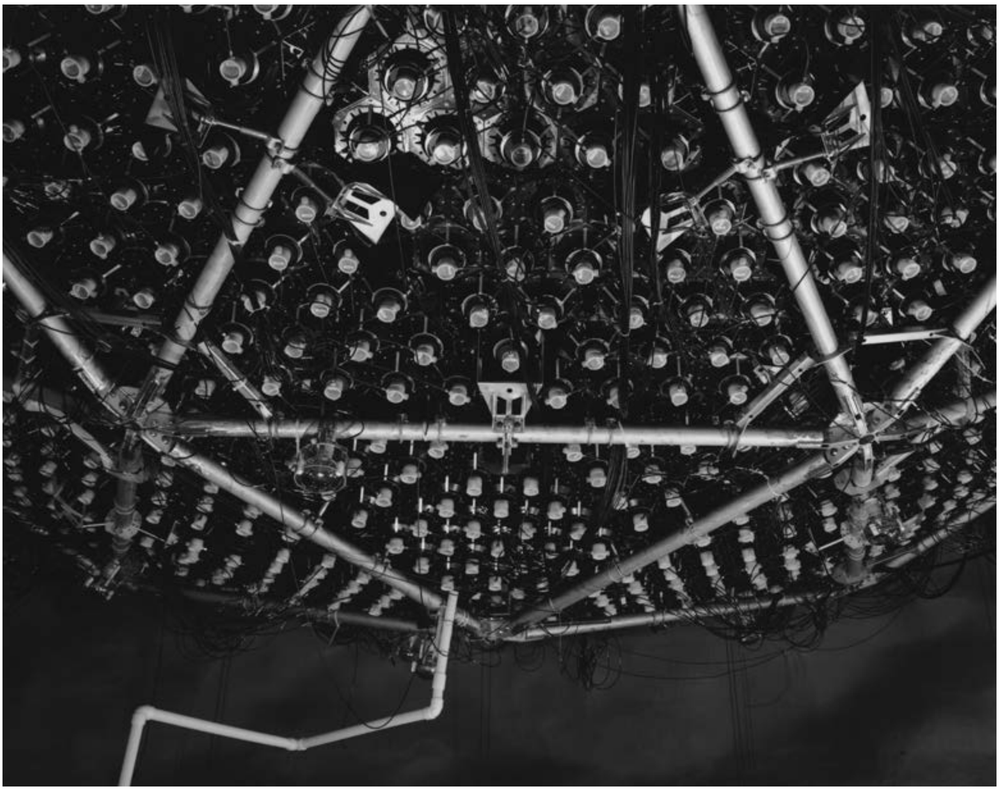
[7] "CERN Press Release." 22 February 2012. *http://press.web.cern.ch/press/PressReleases/Releases2011/PR19.11E.html*

[8] "CERN Press Release." 16 March 2012. *http://press.web.cern.ch/press/PressReleases/Releases2011/PR19.11E.html*

[9] Antonello et al. "Measurement of the neutrino velocity with the with the ICARUS detector at the CNGS beam." arXiv:1203.3433v3 [hep-ex]. 29 Mar 2012. *http://arxiv.org/pdf/1203.3433v3.pdf*

Stephanie **Sallum**

Detector, Sudbury Neutrino Observatory, Ontario, Canada, 2009



Stephanie graduated with a Bachelor of Science degree from MIT in 2012 as an Earth, Atmospheric and Planetary Sciences (EAPS) and physics major. She is now a graduate student in the Department of Astronomy at the University of Arizona. While at MIT she enjoyed working in the Planetary Astronomy Laboratory and playing on the rugby team.

Another day on the job: After the morning safety briefing, you don your thick, reflective jumpsuit, your steel-toed boots, your hardhat and headlamp, and step into the elevator. You're descending 6800 feet. It's still early, so a handful of miners ride down with you; they're headed for 9000 feet below, where they can still find nickel in the active tunnels.

Fifteen minutes later you leave the miners behind and step out onto the damp dirt floor. You turn on your headlamp and look up, casting a circular glow on the dark beams supporting the earthy tunnel walls. Looking down, the puddles flash light back into your dark-adjusting eyes. Stepping forward, you begin the mile-and-a-half hike down the tunnel to the clean room. Having worked up quite a sweat and picked up a bit of mud along the way, you enter the clean room relieved to begin the next step in the process—a hot shower and a fresh outfit.

Professor Joe Formaggio endured this journey and cleansing process every time he worked a shift at the Sudbury Neutrino Observatory (SNO), located 6800 feet below ground in Sudbury, Ontario, Canada. If you ask him to describe it, he'll begin, "It's not like, 'Oh I'll be at the office.'" Professor Formaggio belongs to a group of physicists who from 1999 to 2006 utilized SNO to study neutrinos, elementary particles that, unlike the more familiar electron, do not interact via the electromagnetic force, but by the weak force alone.[1] With a range of 1000 times smaller than a single proton,[2] these weak interactions give neutrinos the ability to pass through vast amounts of matter uninhibited. Thus, in order to detect neutrinos, physicists had to build a detector large enough to even have a chance of interactions taking place. So they designed SNO as a 12-meter diameter acrylic sphere filled with 1000 tons of heavy water (D_2O)[3]—that is, H_2O whose H (normally just a proton and electron) is rather deuterium (D), composed of a proton, neutron, and electron. The Canadian government loaned SNO this water for $1; insuring it cost $1.5 million a year. The cost was well worth it, however, since neutrinos can more easily interact with the loosely bound deuterium than with hydrogen, and SNO's large size increases the likelihood of observing interactions.

SNO's claim to fame lies in the fact that it resolved the Solar Neutrino Problem, which had puzzled physicists since 1968.[3] That year, a physicist named Ray Davis used an experiment called Homestake to measure solar neutrino fluxes, that is, the number of neutrinos striking a given area on Earth at a given time.[4] The sun produces a certain type, or "flavor" of neutrino, called the electron neutrino, when it fuses hydrogen in its core. Two other neutrino flavors also exist, called the tau and muon neutrino.[5] Davis measured only electron neutrinos, and found that the flux was 2.5 times lower than physicists predicted.[1] Resolution of this discrepancy could come from the possibility that the neutrinos oscillate—shape shift between the three flavors, on their path to Earth. Physicists built SNO to measure not just electron neutrinos, but all three flavors.

SNO allowed scientists to distinguish between different neutrino flavors by observing the radiation emitted by different types of interactions.[1] It accomplishes this via the 9438 photomultiplier tubes facing the acrylic sphere, which convert incoming radiation to measurable electrical signals.[1,6] Out of the three ways in which neutrinos can interact with heavy water, two are nonspecific—all three flavors interact—whereas one can only work with electron neutrinos. SNO's ability to observe both the electron neutrino interactions, as well as the nonspecific interactions, led to the resolution of the Solar Neutrino Problem.

In order to accomplish this goal, SNO operated in three phases. The initial phase operated with just heavy water in the sphere, and an intermediate phase followed in which two tons of salt were mixed into the vessel. If you ask Professor Formaggio how they got the salt out again he'll reply, "It's magic." Despite these mysterious purification methods in phase two, the final phase proved most memorable for him, when an out-of-control submarine almost cost SNO its detector.

One of the nonspecific reactions, called the neutral current reaction, could be observed with the installation of two-inch-diameter nickel tubes filled with helium gas called neutral current detectors (NCDs). These NCDs measured 11 meters long; their length required engineers to weld the tubes together using lasers as they lowered the devices into SNO's vessel. The SNO engineers utilized a small submarine, which Professor Formaggio got to test drive during training at Los Alamos—he'll also tell you he was then relegated to "back-up driver" —to lower the NCDs into the sphere. A giant umbilical cord connected a remote control to this chair-sized underwater vehicle, and operators could inflate or deflate air tanks to adjust the buoyancy and thus raise or lower it.

Jaret Heise operated the submarine during that shift. The sub had just reached the bottom of the sphere, taking an NCD anchor with it, when the anchor got stuck. Jaret had flooded the air tanks to get the submarine to sink, and when he began to inflate them, things got out of control. The submarine went completely buoyant, headed on a crash course for the side of SNO's acrylic vessel. While some people in the room began to panic, Heise, a "skilled driver" as described by Professor Formaggio, managed to maneuver the submarine away from the vessel wall and regain control just in the nick of time, a relief for everyone on the job.

By the conclusion of phase three, SNO physicists had what Professor Hamish Robertson, another collaborator and the

US Co-Spokesman for SNO, described as, "solid evidence for solar neutrino flavor change." All three experimental phases showed a greater flux from the nonspecific reactions than from the electron-only reactions. Professor Robertson was present for the first indications of this flavor change; he said, "The room just went silent. We all went, 'Holy cow.'"

Following these results, a magnitude 4.4 earthquake shook the mine, destroying five of the NCDs. Professor Robertson described this as, "a reminder that we were living on borrowed time." Having resolved a 40-year-old conundrum, SNO pumped the expensive and difficult to manage heavy water up to the surface and trucked it back to its owners. Ongoing plans exist for SNO+, a more diverse detector scheduled to replace SNO; who knows what interesting results will surface next.

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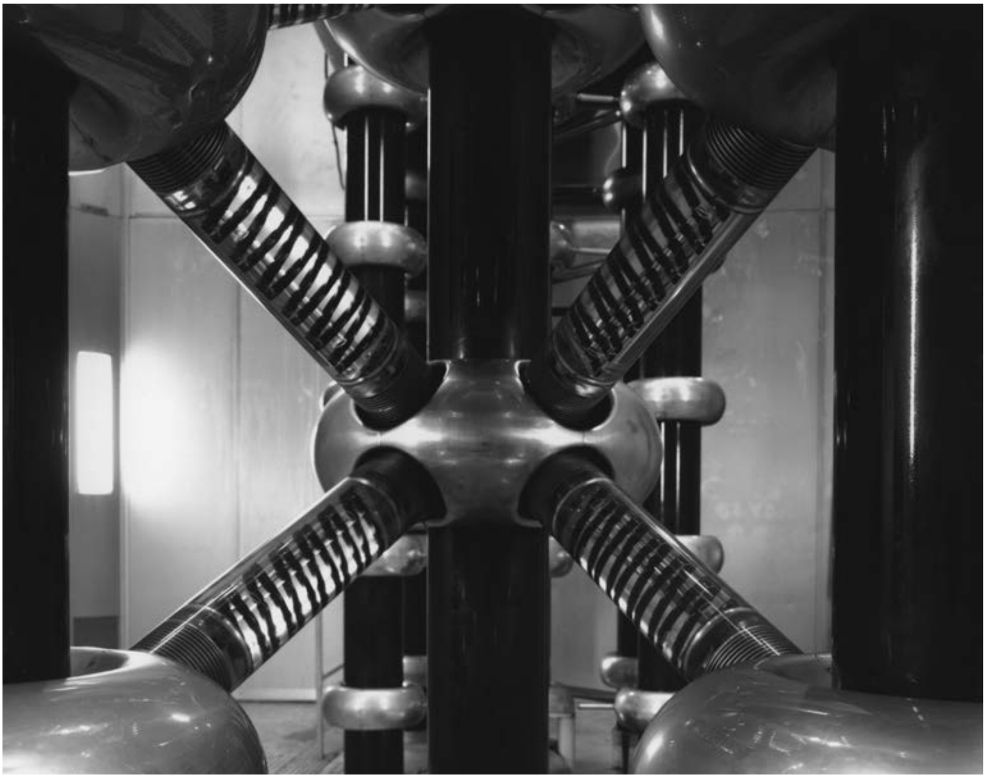
Curran **Oi**

Cockcroft-Walton accelerator, Fermilab, Illinois, 2006



Curran majored in nuclear engineering and physics at MIT, graduating with a Bachelor of Science degree in 2013. Currently, he is building a web-based analytics start-up that he co-founded during his senior year. During his undergraduate years, he enjoyed working on research devoted to building turbulence models for fusion plasmas.

Conventional radiation therapy techniques for cancer treatment use high-energy protons and photons. At Fermilab, Dr. Thomas Kroc researches neutron therapy, which is three times more effective than protons or photons at killing cancer cells.

Since it first began neutron therapy treatment in 1976, Fermilab has treated over 3000 patients, and it continues to treat people today.[1] Neutron therapy is primarily used to treat prostate cancer, though it is also used for salivary gland cancer and some sarcomas. To explain why neutron therapy is an interesting avenue of research, Dr. Kroc said, "Neutron therapy is particularly good at treating radiation-resistant tumors, so it is best at treating those tumors which do not respond well to conventional radiation techniques, like photon therapy." If improvements can be made to the neutron beam targeting and radiation dose localization, neutron therapy could become a more prominent treatment option for cancer patients.

The neutrons used to treat tumors at Fermilab come from the LINAC, Fermilab's linear accelerator. The journey begins, however, in Fermilab's Cockcroft-Walton accelerator, depicted in this photograph, where hydrogen ions are accelerated before being separated into proton and electron beams. The proton beam is then bent from the accelerator and aimed at a target of beryllium. When beryllium interacts with protons it produces neutrons, particles with no electric charge. This neutron beam is transported in the LINAC before being aimed at patients' tumors by means of slabs of material called compensators and collimators.

Imagine the atoms and molecules in your body as having a small solid core, the nucleus, surrounded by a sea of tiny buzzing particles, electrons. When Fermilab's neutrons enter the body they are moving very fast, at approximately one third the speed of light. They are smaller than nuclei and they whiz through the sea of electrons. Occasionally colliding with electrons and nuclei, the neutrons usually glance off at small angles. With each collision, they lose a small fraction of their energy and are deflected off their path a bit. Most neutrons' journeys end when they are "absorbed" by a nucleus.

These speedy neutrons kill cells by damaging DNA. While they zoom through our bodies en route to the tumor, they collide with various molecules in the body. Neutrons do most of their damage by two mechanisms: direct and indirect.

By colliding with DNA molecules, neutrons directly damage the DNA by breaking DNA strands. In order for cells to function properly, they need to repair themselves. In most tissues in the body, like skin, there is a high rate of cell turnover: many cells die or are shed and new cells are produced by cell replication in the body to take their place. If not repaired, many cells damaged by neutrons or other forms of radiation will often die or simply lose their ability to replicate again.

Another method for damaging tissue is indirect: when neutrons pass through tissues in the body, they interact with water molecules, which are abundant in cells. Through water radiolysis (the splitting of water) hydrogen radicals, hydroxide radicals, and other molecules are produced. Of these products, the free radicals, both hydrogen and hydroxide, are highly reactive and seek desperately to steal hydrogen atoms from other molecules, including DNA molecules. When the free radicals attack DNA they create damage that needs to be repaired by the cell. When this damage is extensive and goes unrepaired, the cell dies.

The excessive damage neutrons do to healthy tissue makes neutron therapy less desirable than photon or proton therapy. This is disappointing because neutrons are about three times more effective than protons or photons at killing cells, so they could be a great weapon if they could be targeted more selectively at cancer cells.

Protons are like positively charged neutrons, so they scatter like neutrons while moving through tissue, though they also undergo electromagnetic interactions because they carry charge. This means they are attracted to the negatively charged sea of electrons and repelled by the positively charged nuclei of nearby atoms. Due to these additional interactions, protons slow down in tissue differently from neutrons; as a result, protons are much better at avoiding healthy tissue and delivering most of their dose (energy deposited per mass of tissue) directly to the cancer tissue. Photons can similarly be targeted to tumors much more accurately than neutrons. Presently, this advantage outweighs the fact that neutrons are more effective at killing cells.

While photon and proton treatments have been shown to have major advantages over neutron therapy, Dr. Kroc is hoping some of his present research can help to promote neutron therapy. He is currently working on techniques to guide the neutron beam to minimize the damage to peripheral tissue and using Monte Carlo simulation methods to determine the optimal neutron energy for treatments. The neutron beam can be targeted more accurately by using specialized collimators and compensators. Collimators absorb stray neutrons in order to guide the beam in a straight line. Compensators are wedges of absorbing material placed between the beam and the patient; more dose is delivered where the wedge is thinner and less where it is thicker. In his research, Dr. Kroc is working on developing "multileaf" collimators for neutron beams, which use several layers of blocking material to focus the beam. Perfecting collimators and compensators will allow the dose from neutrons to be more accurately focused on tumors alone, sparing more of the healthy tissue.

While Dr. Kroc is passionate about his field of research, he believes that without major advancements to neutron therapy in the next few years there is a high probability it will simply fade away. When asked what needs to be done in order to save neutron therapy he explains, "If [neutron therapy researchers] can effectively implement collimators and compensators, get more funding, and do a few more studies, [they] can reestablish neutron therapy." This will be a tall task considering there are only a handful of people in the country engaged in this research, with Dr. Kroc being the only individual at Fermilab's neutron therapy facility principally devoted to the project.

Though few people are devoted to researching neutron therapy, it is still a useful treatment for some tumors. When I asked Dr. Kroc to tell me what he would like to share if he had the opportunity to address the public he said, "Neutron therapy is often presented as a fallback treatment. The body has an overall tolerance to radiation. If you've used it up with conventional photon therapy then you cannot retreat that area with neutrons. Neutrons are very good at treating some cancers so neutron therapy should be considered from the beginning when planning treatment for tumors." Neutron therapy is particularly good at treating advanced prostate cancer, salivary gland tumors, and some sarcomas; depending on the specifics of the tumor, neutron therapy might be the best form of treatment.

[1] *http://www-bd.fnal.gov/ntf/*

THANK **YOU**

This project was supported by MIT Alumni Class Funds, which are designated to support innovative projects in undergraduate education: http://web.mit.edu/alumnifunds/

The Class of 1951 Fund for Excellence in Education

The Class of 1955 Fund for Excellence in Teaching

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Additional support was also provided by the MIT Department of Physics.

This publication, produced by the MIT8.226 class under the direction of Professor Janet Conrad, accompanies the exhibition:

MIT museum

STANLEY GREENBERG: TIME MACHINES

Kurtz Gallery for Photography, MIT Museum
September 13, 2013 – March 30, 2014
Exhibition curated by Gary Van Zante

These essays were written as an exercise for

MIT Class 8.226: 43: Orders of Magnitude
http://stellar.mit.edu/S/course/8/sp12/8.226/
Professor J.M. Conrad

Every day, across forty-three orders of magnitude in distance scales, scientists are making discoveries that affect society.

To support sound public policy about the issues which arise from this research, it is essential for physicists to engage in the public debate.

This class explores some of the questions that our present scientific achievements raise, both for our own community and for the public at large. By considering topics as diverse as the climate change and nuclear nonproliferation, this class makes the case that physics is a necessary part of the national discourse.