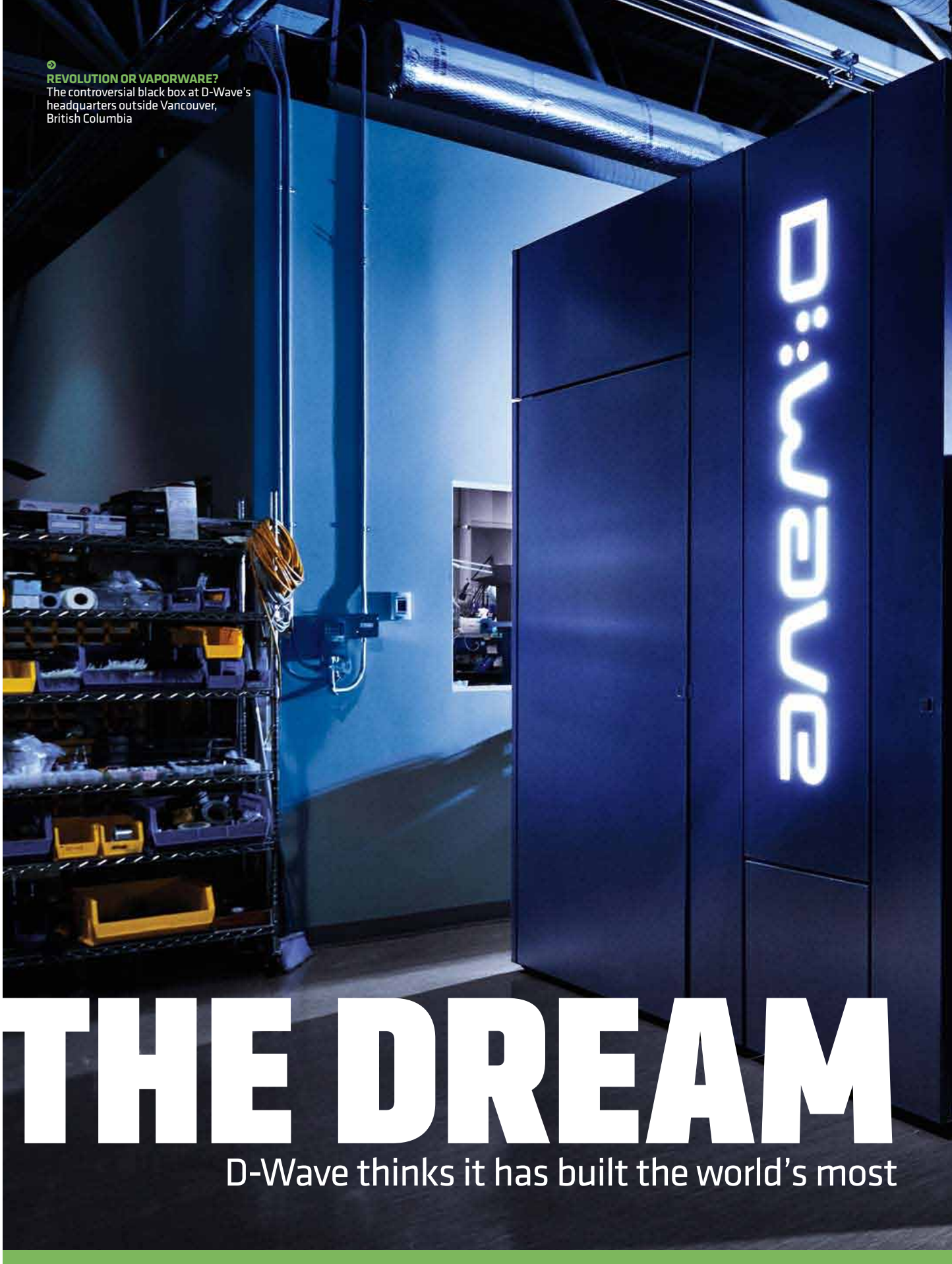


REVOLUTION OR VAPORWARE?
The controversial black box at D-Wave's headquarters outside Vancouver, British Columbia

THE DREAM

D-Wave thinks it has built the world's most

MACHINE

powerful computer. Mother Nature has other ideas

BY WILL BOURNE PHOTOGRAPHS BY SPENCER LOWELL

"I wasn't smart enough,"

says Geordie Rose of his days getting his physics Ph.D. at the University of British Columbia. "Mathematicians and physicists can wrap their heads around things that are really hard to understand for a normal human. They would be talking at three miles a minute about some 28th-dimensional whatnot, and I'm like, 'I have no idea what you're talking about.' "

The average visitor to D-Wave Systems, the computer maker Rose co-founded in 1999, probably feels the same way. Housed in an unremarkable Vancouver office park, behind the British Columbia Automobile Association building, D-Wave has set out to build—and sell—a machine many computer scientists believe exists only in theory. There are other supercomputer makers, of course, but their machines follow the familiar dynamics of Moore's law. Rose's device, however, is powered by the brain-knotting concepts of quantum physics.

That makes D-Wave a place of otherworldly extremes: computing speeds "100,000 times faster" than traditional computers, temperatures "150 times colder than interstellar space," time spans longer than "the age of the universe." And the potential payoff is just as surreal. Although many physicists doubt that a quantum computer would be all that useful except as a way to study quantum physics, D-Wave believes it would change the very definition of *impossible,* that the world's computing infrastructure would be transformed overnight, with a quantum cloud forming to handle some of our gnarliest computational challenges. Problems that have been unsolvable with current computers—whether molecular modeling for drug development or "optimization" problems routinely encountered by logistics-dependent companies like UPS—would suddenly give way. Existing industries, including software design, nanotech, and machine learning, would be transformed, and massive new markets would grow up around them. In D-Wave's vision, a quantum computing age would seem as foreign in 2014 as today's digital age would to someone living under Herbert Hoover.

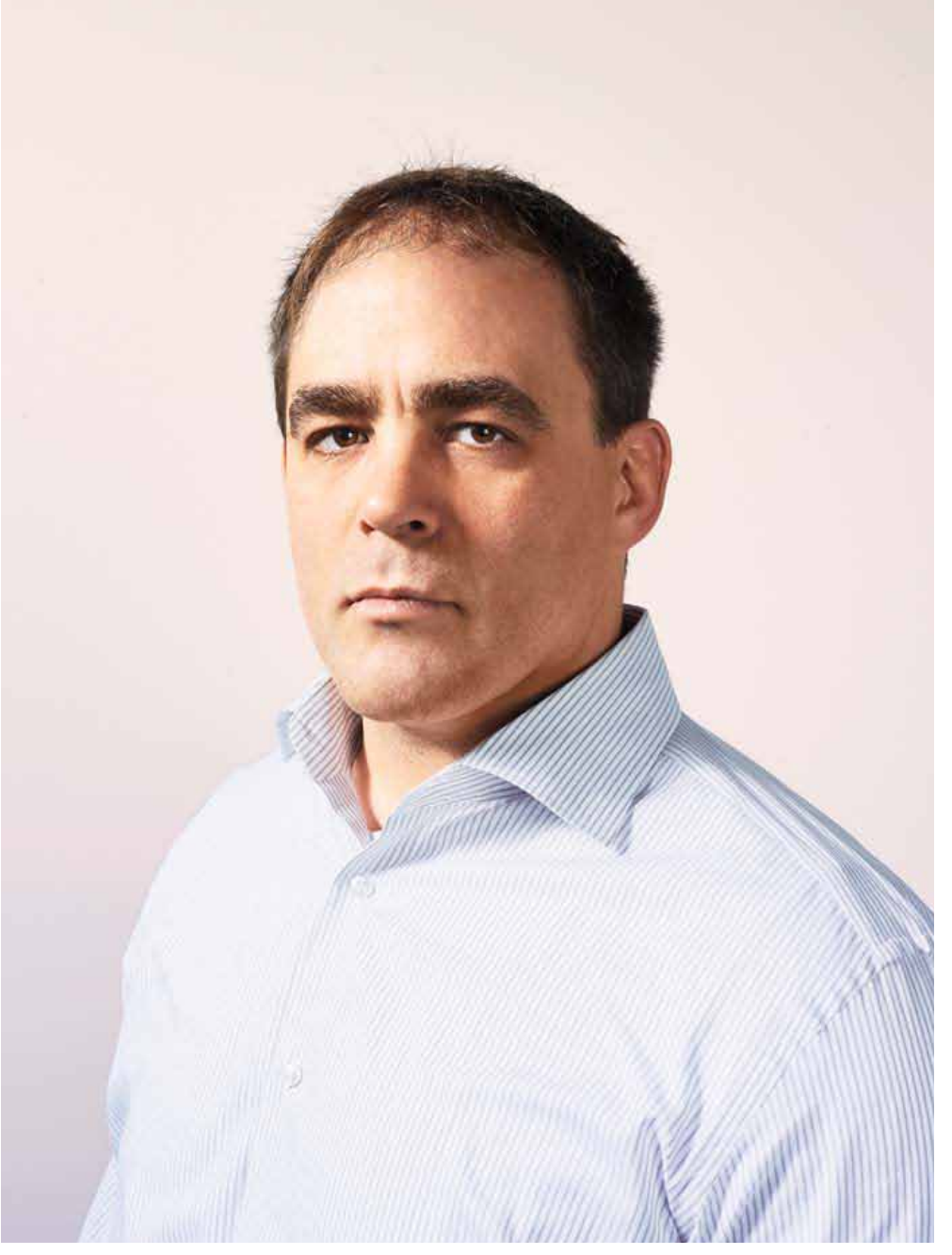
Not surprisingly, building such a computer entails a series of absurdly difficult theoretical and engineering challenges. And yet, a decade and a half after its launch, D-Wave has come out the other side with a 10-foot-tall refrigerated black box that does more than almost anyone thought possible. Along the way, D-Wave has acquired the trappings of a technology powerhouse: state-of-the-art superconducting expertise, a team of 35 in-house mathematicians and physicists, a wafer fabrication deal with Cypress Semiconductor, and nearly $130 million in venture capital. D-Wave has a patent portfolio ranked No. 4 worldwide in the computer systems category by *IEEE Spectrum* in 2012—after only IBM, HP, and Fujitsu. It has two blue-chip customers: Lockheed Martin picked up a D-Wave One in May 2011, in a $10 million multiyear "lease" deal; last May, Google and NASA went in together on the next-generation D-Wave Two in a similar arrangement valued at about $15 million. (Lockheed got what Rose calls a "forklift upgrade" at about the same time, for another $10 million.) And D-Wave has Rose, who at 42 has now bet well over a decade of his life on the company.

Rose happily recites these achievements, and he is perfectly comfortable striking a heroic pose. He is given to forecasting, for example, that his company will effectively become the next Microsoft. But the mythic figure Rose may most resemble in the end isn't Bill Gates but Icarus. Questioning D-Wave's real accomplishments has become a cottage industry, with physicists and computer scientists worldwide debating whether the company's black box is a real quantum computer and whether it does—or could ever do—anything an ordinary computer can't. At one time, Rose could toss off such criticism as the carping of propellerheads. Not any more: With his $15 million machine now on the market, he has to prove that it can be useful on a commercial scale. Now it is becoming clear that mere determination may not be enough, that even a fighter like Rose can't overthrow the laws of physics.

QUANTUM PHYSICS IS THE study of very small things, the atomic and subatomic scale where nothing behaves as you think it should. There, apples don't fall from trees with a satisfying thump—they appear in multiple trees at once, and on the ground, and everywhere in between. If classical physics examines the way things seem to behave, quantum physics looks at how protons, electrons, and other invisible doodads really do behave at the most basic level. What it has found is almost impossible for normal humans to believe, let alone understand.

The idea of harnessing quantum mechanics to create a so-called universal quantum computer first entered the mainstream via physicist Richard Feynman in 1982. In a traditional computer, the standard bit of information is binary—it can be either a *1* or a *0*. Feynman theorized, however, that a quantum bit, or qubit, would take advantage of quantum behavior and be capable of being a *1,* a *0,* or both simultaneously. This ability to hold more values at a given time should, he reasoned, translate into a dramatic increase in computing power.

For decades, scientists have worked to build qubits that perform as Feynman imagined, only to find that "quantum superposition"—the state of being both a *1* and a *0* simultaneously—is incredibly hard to maintain. The outside world



THE GRAPPLER
In his quest to build a quantum computer, former Olympic wrestling hopeful Geordie Rose is tackling a problem that stumped a generation of physicists before him.

"Building a business around this was laughable. The chance of it working was zero."
—GEORDIE ROSE

constantly interferes in the form of vibration, temperature, sound waves, light; just about any perturbation leads to "decoherence" that commits the qubit prematurely to one state or another, robbing it of its quantum juju. As with conventional computers, the power of a quantum computer is a function of the number of qubits on the chip—but unfortunately, the more qubits, the more likely it is that decoherence will swamp the system. To date, every attempt to pick the lock on a universal quantum computer has stalled out at a handful of qubits. The closest science has come is a system that can't factor a two-digit number as quickly as a 10-year-old child. (A universal quantum computer would in theory excel at factoring very large numbers, destroying most digital encryption schemes—hence the interest of the National Security Agency, as recently revealed by Edward Snowden.)

Into this unpromising scenario, circa 1999, strode Geordie Rose. Rose doesn't look like your average physics Ph.D. He looks like a corn-fed, detoxed Colin Farrell, with extra eyebrow, a barrel chest, and arms capable of inflicting serious hurt. Born in Tanzania, Rose spent his first two years in Moshi, a jumping-off point for the Ngorongoro Crater, where his father was a wildlife-management officer. When his father brought the family home to his native Canada, it was to Wawa, a small town in northern Ontario. "So, when I was very young," he says, "basically we lived in the bush."

Rose moved around a lot growing up, eventually getting recruited to wrestle at McMaster University in Ontario. He was on the winning 1994 Canadian national championship team and says he was an alternate for the 1996 Olympic Games. "I really wanted to compete at the Olympics, but it never happened," he recalls glumly. "It's a little bittersweet, but you do what you can."

After graduating from McMaster, Rose pursued a doctorate in physics at the University of British Columbia, where he met the three co-founders of what would become D-Wave. The most important of them was Haig Farris, a central figure in Vancouver's transformation into a tech hub; his course on entrepreneurship, Rose says, "was the first time I had ever seen anything related to business. I remember thinking that the people who were coming through and talking to us, I felt I could be like that—whereas I *knew* I wasn't as good as the academics at the science."

Over the next couple of years, Farris and Rose struck up

a friendship, and Rose started talking about quantum computing, a concept he had encountered in his thesis work. "Four to six months later, we had a business plan," he says, and in April 1999, D-Wave was founded. (Farris remains a co-founder and board member; the other two co-founders have left the company.)

Quantum computing was still a highly theoretical, arch-nerd pursuit. "Building a business around this idea was laughable," says Rose in a D-Wave conference room, his scary arms popping under a tight black T-shirt. "The chance of it working was zero."

Rose and his partners initially planned simply to corner the market on expertise in quantum computing, then "partner with or be acquired by" someone who was building an actual machine. Farris had thrown Rose a few thousand dollars in seed money, and they raised half a million (Canadian) from local angels; over the next few years, they pulled in another $4 million from Vancouver-based start-up funds and the Business Development Bank of Canada—money they used to lock up as much intellectual property as they could. "[The scientists] basically gave it to us for free," Rose says. "They thought, Hey, these guys are going to give us $50,000 to do what we're going to do anyway. We need to sign away our IP? I don't care." All of that seeded what is now the biggest IP portfolio in the world in quantum computing.

MUCH AS HE RELIED on academic researchers, Rose never had much patience for their grinding pace. He wanted to ring in the age of applied quantum computing. He wanted to help create a new industry. He wanted to get rich.

Then D-Wave ran out of money.

By late 2002, Draper Fisher Jurvetson, the archetypal Sand Hill Road venture capital firm, had already turned D-Wave down. But Rose had noticed that managing partner Steve Jurvetson was drawn to companies most investors shied away from, companies with "a 5 percent chance of success," as Rose puts it. Rose also knew that Jurvetson was interested in nanotechnology, a field that would instantly be transformed by a working quantum computer. "You could tell he wanted to do the deal," Rose remembers. "So I kind of invited myself in to his office. We had a term sheet the next week."

So brazen was Rose that Jurvetson didn't even know D-Wave was in trouble. "I didn't realize the *paaiiin* he was in," Jurvetson says with a laugh, "the *anxiiiiety,* whether this was one of his *laaaast* shots to get funding. All that context was lost on me because he's projecting into the future, projecting strength, all that. So I have to chuckle: I actually wasn't even aware that he'd been in a tough spot!"

DFJ led a $7.1 million (U.S.) round, transforming D-Wave's mission in the process: The company was no longer just looking to gather IP in the hope of flipping it down the road. DFJ and other investors were banking on D-Wave to build the world's first commercial quantum computer. Rose was suddenly responsible for bringing to market a technology that an entire generation of physicists couldn't even get to work in a lab.

One of Rose's early decisions was not to try to build the "universal" machine that had frustrated so many of his predecessors. Instead, he decided on a more limited design that would target only certain sorts of problems, including optimization, machine learning, and molecular modeling. Even if he succeeded in only that more scaled-back goal, he would be a very rich man, indeed.

The DFJ seal of approval eventually got the venture dollars pouring into D-Wave from Goldman Sachs, Jeff Bezos, and the CIA's venture arm, In-Q-Tel. At the same time, even Rose's downscaled project was so intriguing to theoretical physicists and mathematicians and hardcore engineers that he could draw talent from the most famous brainiac centers on earth: NASA Ames, the Jet Propulsion Laboratory, Santa Fe Institute, MIT, Cal-Tech, Germany's Max Planck Institutes, and the Moscow Institute of Technology.

D-Wave spent the next two years in "a little lab at UBC," building its first qubit, using a design developed by a number of professors at MIT, including Seth Lloyd, a ponytailed professor of mechanical engineering who calls himself "probably the first person to propose how to build a

CONTINUED ON PAGE 112 ►

QUANTUM BITS

Since 2007, MIT computer science professor and "chief D-Wave skeptic" Scott Aaronson has been at the center of the debate about the company. A few choice morsels from his blog-cum-soapbox, Shtetl-Optimized:

—

ON ROSE'S CRITICISM: I find it amusing that Geordie is now trying to spread the meme that I've been "wrong exactly 100 percent of the time about everything." I admit that I've been wrong in underestimating human credulity and herd behavior.

—

ON GOOGLE'S PICKING UP A D-WAVE TWO: Imagine yourself in command of a $100 billion empire, when one of your subordinates comes babbling to you about a new startup that's building interdimensional flux quantum jigga-transponders. A perfectly reasonable response would be: "I don't understand this. I don't have time to understand it. In fact, it sounds a bit fishy, so what the hell, throw $10 million at it just in case. Next agenda item!"

—

ON MAGICAL THINKING: Commenters on D-Wave threads remind me of the kid who thought there were little men inside his TV. Hearing this, the kid's engineer mother took a few hours to explain to him all about digital signal transmission, liquid crystal displays, etc. The kid listened with interest, asked intelligent questions, and seemed to understand. But finally he said: "But, Mom, there must be at least a few little men inside the TV, right?"

—

ON THE LOAD HE CARRIES: I can either respond [to critics] and get called an asshole or not respond and get called a coward. Or I can respond when and how it's comfortable for me, and get called both an asshole and a coward. So, in summary, I no longer feel like I know how to handle the burden of being right.

–LYDIA BELANGER

THE DREAM MACHINE
CONTINUED FROM PAGE 104

quantum computer." That phase flamed out at a much-anticipated 2007 demo at the Computer History Museum in Mountain View, California. With his "quantum computer" being run remotely from Vancouver, Rose took the stage and had the thing "solve" a Sudoku puzzle, among other problems. But D-Wave refused to let anyone under the hood of its black box and offered no proof that anything "quantum" was happening at all. The event produced what Lloyd calls the "first D-Wave backlash. It was really quite bogus. [D-Wave] made these really exaggerated claims about the kinds of problems they could solve."

Rose retreated to his little lab. It would be four more years of iteration—including more than 20 distinct chips—before the sale of the D-Wave One to Lockheed.

ROSE IS A MASTER of the strategic adjustment, both in his business and in his conversations with the press. He pivots, retools, scales back. But no amount of dancing will change the basic question the market will ultimately force him to answer: Is his computer better at something—anything—than the ones we have now? Will it ever be?

A commercial computer is judged by how fast it solves a given problem. So when Google was deciding whether to buy the D-Wave Two in 2013, speed was central: "Several times we'd tried to get Google to buy one of our machines," Rose explains. "The first two failed. One of the conditions of the purchase on this third [try] was that Google be allowed to set a bunch of acceptance criteria."

It was an understandable request. But authorizing the tests was "a really difficult decision to make," says Rose, "because we didn't know what the results would be." He knew a bad showing could finish off D-Wave. At the same time, declining Google's challenge would cost D-Wave its ideal customer, one that could give the business a whole new kind of traction.

Rose bowed to the inevitable. He hired Catherine McGeoch, a computer-science professor from Amherst College, to conduct three benchmarking tests comparing the D-Wave Two's chip with a conventional PC running off-the-shelf software. (If the computer survived McGeoch, Google reserved the right to try to reproduce her work on its own.) He couldn't have hoped for much better results than the ones McGeoch published in May 2013: The D-Wave machine had been "3,600 times faster" on one test than the PC running commercial "solver" software, she said, and about equal on the other two.

If D-Wave's future had been hazy, the clouds seemed to part with McGeoch's report. The press worldwide seized on the 3,600 figure: *D-Wave's Quantum Computing Claim Gets Boost in Testing,* announced the relatively cautious *IEEE Spectrum,* while *The New York Times* went for broke with *A Quantum Computer Aces Its Test.* Google took its machine home—it now lives at NASA's Ames Research Center in Silicon Valley—and D-Wave ran a long-awaited victory lap. Referring to his computer, Rose wrote on his blog: "The way I thought about it was that we'd have succeeded if: (a) someone bought one for more than $10M; (b) it was clearly using quantum mechanics to do its thing; and (c) it was better at something than any other option available. Now all of these have been accomplished."

About six months later, McGeoch accepted a job at D-Wave as the "benchmarking team lead."

COMPANIES SUCH AS GOOGLE and Lockheed can't afford to be late to an emerging technology with the potential—however speculative—of quantum computing. As Steve Jurvetson puts it, companies could purchase a D-Wave "just to be on the learning curve," laying the foundation of what might become a radical competitive advantage. If the bet goes bust, that $15 million is simply a cost of doing business.

In fact, although the D-Wave's chip is still tiny at 512 qubits, Google is reported to be using it already, albeit in tandem with its traditional servers, in the Google Glass technology that distinguishes a wink from an involuntary blink. NASA, meanwhile, hopes to use its D-Wave to discover exoplanets. And Lockheed Martin told *Inc.* it plans to deploy the device one day for software "verification and validation," as one executive said, examining vast amounts of code to assess whether the software would perform as intended—"whether the plane would fly," an impossible task for today's computers.

Yet even as the "3,600 times faster" figure was sweeping the globe, there were signs that the future might be more complicated. A month before McGeoch published her results on the D-Wave Two, a paper was released by a team of scientists who had been studying Lockheed's D-Wave One at the University of Southern California. The team found that the speed advantage McGeoch would report was entirely attributable to the off-the-shelf software chosen for the comparison. According to one co-author, Matthias Troyer, a tidy and precise computational physicist from Zurich's Institute for Theoretical Physics, one of his postdocs quickly wrote code that could match the speed of both D-Wave One and D-Wave Two. Other scientists have since done the same.

If speed is the criterion of success, it seems, D-Wave isn't there yet. But all the talk about raw speed misses the point, says Troyer. What his tests reveal, he explained to an audience at the Microsoft Research Faculty Summit last July, is that as D-Wave packs more qubits onto its chip—from the 128-qubit D-Wave One to the current 512 qubits to the thousands that will be needed to take on "hard" optimization and machine learning problems—the time needed to solve the problem appears to rise exponentially, in precisely the same way it does on a conventional computer. There appears to be no speedup over

existing machines on the very problems the D-Wave is intended to solve.

Troyer says he has tried to help D-Wave understand his results, going so far as to send his team's "faster" code to Vancouver. "I sent it to them, they tested it, and it works," he says. "And then...silence." He believes scientific rigor and transparency are being clouded by Rose's commercial ambitions and "hype," and he fears that Rose's overreach could tarnish the entire field of quantum computing research, setting it back years.

Troyer's co-author, Daniel Lidar, is a professor of electrical engineering, chemistry, and physics at USC and is generally considered to be one of the pro-D-Wave authors on the paper. Lidar also happens to be the scientific director of the USC-Lockheed Martin Quantum Computation Center. In other words, he says he has been "involved from the very start in the whole engagement between Lockheed and D-Wave."

Choosing his words painstakingly in a phone interview, Lidar says the "time-to-solution" issue Troyer points to suggests that decoherence is a clear and growing threat to the D-Wave machine. He explains that although he has seen some encouraging results in the lab, "solving" D-Wave's decoherence problem is "an extremely tall order and is likely to require substantial changes to the existing D-Wave design." Asked whether it would be appropriate to call the state-of-the-art D-Wave Two a science experiment as opposed to a product, Lidar replies, "I think that's fair."

"THAT'S TOTAL BULLSHIT," SAYS Rose, on hearing that his computer may have a flaw—possibly a fatal one—in its architecture. Suddenly he sounds not at all like the man who felt intellectually inferior back in grad school: "That's just wrong. That's a misunderstanding of the underlying physics of the problem."

Rose says the misunderstanding stems from his highly pedigreed colleagues' mistaken belief that "what they're measuring from the machine is some fundamental property of nature. It's not." He adds that D-Wave has already achieved more than almost anyone thought possible. "The physical artifact we've built—in 10 years, with $100 million—is performing at par with 60 years and trillions of dollars of investment" in traditional computer technology, he says, blithely contradicting his own oft-repeated claim that his artifact is actually superior. "That's a remarkable thing."

Many of Rose's critics readily agree that it is remarkable he's built a machine that works at all. Even some skeptics refuse to bet against him. Like any good scientist, Troyer won't guess about D-Wave's future. And MIT's Lloyd says D-Wave has proved some of his predictions wrong in the past. "Who knows?" what they'll pull off, he says, before conceding, "D-Wave is not my idea of a good investment."

D-Wave won't say whether new customers are lining up or when they might pull the trigger. But the company tells *Inc.* it is now "looking to raise between $40 million and $60 million, which we believe will be our last round before a breakeven financial scenario." It says its current investors are "in this for the long term. They're great investors."

As for Google, the company didn't respond to requests for comment before a version of this story went online in early January. But on January 19, it posted a progress report. Though the Google Quantum A.I. Lab Team was clearly enjoying its machine, it noted that "at this stage, we're mostly interested in answering the question: Can we find a set of problems where the [D-Wave] hardware outperforms the best known algorithms running on classical hardware?" It added that although "there are problems for which the [D-Wave] hardware does much better" than a given classical solver, taken together, classical solvers can still do anything the D-Wave can do. The blog post also laid out "a list of other hardware aspects still limiting performance that future iterations will need to improve," including "longer coherence times" and "error correction"—the very concerns Troyer, Lidar, and others have been raising. (The post also confirmed that Troyer's postdoc coder, Sergei Isakov, now works for Google.)

"We are going to become one of the most significant companies in the world."
—GEORDIE ROSE

If there is no detectable scent of fear hanging over the D-Wave offices, that's because, in Rose's mind, there has "never been a question that this thing will succeed." Engineering will win the day. He and his crew will iterate the nonbelievers into submission. "In 10 years, virtually everybody in the world will be using a product that was designed on one of our machines," he vows. "We are going to become one of the most significant companies in the world. I'm pretty sure of that now. It's just a matter of time."

Time, unfortunately, has a tendency to take down even the fiercest opponent. Acknowledging the challenges ahead for D-Wave, Steve Jurvetson allows that "this is a watershed moment." For Rose to succeed on a level that will get him and his investors paid, everything will have to go their way. That's starting to look like a wager only a venture capitalist would take.

—

WILL BOURNE *is an* Inc. *editor-at-large. His last article was on GitHub.*

PRINTED IN THE USA. INC. (ISSN 0162-8968) is published monthly, except for combined July/August and December/January issues, by Mansueto Ventures LLC, 7 World Trade Center, New York, NY 10007-2195. Subscription rate for U.S. and Possessions, $19 per year. Address all subscription correspondence to *Inc.* magazine, P.O. Box 3136, Harlan, IA 51593-0202; 800-234-0999; icmcustserv@cdsfulfillment.com (U.S., Canada, International). Please allow at least six weeks for change of address. Include your old address as well as new, and enclose if possible an address label from a recent issue. Single-copy requests: 800-234-0999. Periodical postage paid at New York, NY, and additional mailing offices. Canadian GST registration number is R123245250. Canada Post P.O. Box 867, Markham Station Main, Markham, Ontario L3P 8K8. POSTMASTER: Send address changes to *Inc.* magazine, P.O. Box 3136, Harlan, IA 51593-0202. MARCH 2014 VOL. 36 NO. 2