# ToughTech

*A publication by* The Engine, built by MIT

QUANTUM COMPUTING

FUSION ENERGY

SPRING 2018

THE ENGINE
Built by MIT

# A home for Tough Tech founders.

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**Tough Tech Publication 01**

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**THE ENGINE**
Built by MIT

## The Engine, built by MIT, helps founders create the next generation of world-changing companies.

## We're here to empower and inspire those at the forefront of their fields – scientists, engineers, entrepreneurs, and visionaries – with long-term capital, knowledge, and the specialized infrastructure they need to thrive. It's our job to help bridge the gap between discovery and commercialization; to bring disruptive technologies from the lab into the light.

### THE ENGINE FUND

We provide long-term capital that prioritizes breakthrough ideas over early returns, because Tough Tech takes time.

### THE ENGINE PROGRAM

Commercialization is nuanced and intimidating. We help founders navigate this landscape by providing them with entrepreneurial knowledge, expertise, inspiration, and guidance.

### THE ENGINE ROOM

From equipment to labs, we ensure that founders and their teams have access to the resources they need to continue their work efficiently and economically.

### THE ENGINE NETWORK

We are a community of like-minded individuals and corporations working together to guide, advise, and expand the possibilities of Tough Tech companies.

## OUR STORY

Built by MIT, The Engine was a response to a challenge the university's leaders heard from faculty and alumni entrepreneurs: finding the sustained support to develop Tough Tech ideas was nearly impossible. MIT President L. Rafael Reif articulated the problem in a Washington Post op-ed from May 2015.

> *It takes time for new-science technologies to make the journey from lab to market, often including time to invent new manufacturing processes. It may take 10 years, which is longer than most venture capitalists can wait. […]*
>
> *Today, our highly optimized, venture-capital-driven innovation system is simply not structured to support complex, slower-growing concepts that could end up being hugely significant—the kind that might lead to disruptive solutions to existential challenges in sustainable energy, water and food security, and health,*

The op-ed defined the need for a new kind of organization—an "innovation orchard"—specially designed to help Tough Tech startups achieve sustained success.

From this first sketch of an idea, President Reif challenged MIT's leadership to understand what more the institution could do to spur invention and regional development. Could they create an environment that empowered innovators to develop breakthrough ideas and deliver them to the world?

For over a year, Israel Ruiz, Executive Vice President and Treasurer of MIT, spoke to founders, entrepreneurs, and companies to explore how the university could realize Reif's vision. The answer was simple: long-term capital, access to specialized instrumentation, and entrepreneurial expertise.

Born from these experiences and connections, The Engine emerged as the demonstration of what an innovation orchard might be. Headquartered close to Kendall Square—famously, "the most innovative square mile on the planet"—The Engine's defining principle is to support Tough Tech founders who seek to create materially positive impact on society. By prioritizing breakthrough ideas over early profit, The Engine seeks to cultivate new fields and push the boundaries of innovation.

# What is Tough Tech?

## Tough Tech is transformative technology that solves the world’s important challenges by uniting breakthrough science, engineering, and leadership. Tough Tech is worth the wait.

OUR AREAS OF FOCUS

▲
ADVANCED MANUFACTURING

BIOTECH & LIFE SCIENCES
▼

▲
DEEP SOFTWARE

ENERGY
▼

▲
INTERNET OF THINGS

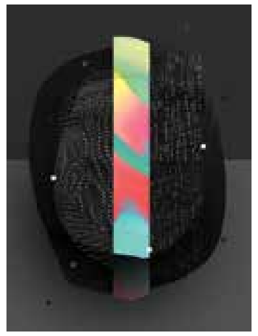
ADVANCED MATERIALS
▼

▲
ROBOTICS

SEMICONDUCTORS
▼

▲
SPACE

QUANTUM COMPUTING
▼



...AND THE INTERSECTION OF OTHER NEW TECHNOLOGIES

A NOTE FROM OUR CEO

# A Grand Leap of Faith

**Katie Rae**
*CEO & Managing Partner, The Engine*

No matter how compelling the science, how compelling the technology, how compelling the invention, there is never the guarantee of a compelling business. The leap from the world of the bench to the world of the balance sheet is a long and uncertain one. But it is one, when taken with intention and perspective, that stirs new questions and challenges, bringing with it greater innovation and investment. It is a leap that is as necessary for individual technologies as it is for the ecosystems in which they reside.

These articles explore the intersection of potentially world-changing innovations and the realities of their commercialization. They investigate the challenges of scalability, repeatability, economies of scale, regulation, and others, and their impact on the evolution of a technology. They hope to showcase why some ideas must be privatized to reach their world-changing potential.

We selected quantum computing and fusion energy as features in our first publication precisely  because we believe these technologies are in profound periods of transition.

Quantum hardware is continuing to become more refined and practical, and supporters of the field now argue that quantum computing is “inevitable.” As more applications for the inherently quirky nature of quantum computing are becoming apparent, it is also clear that the technology faces profound challenges around error rates, scale, and speed. These challenges will be faced head-on as quantum computing moves from conceptual lab science to commercial reality.

For those in fusion science, the pressing threat of climate change has created a moral and existential imperative to invent a functional net-positive fusion reaction and to bring that technology to market in a manner that’s safe, reliable, and cost competitive. Over the past decade, advances in plasma science, material science, and computation have created a remarkable set of tools and understanding that bring the prospect of commercially-viable fusion closer than ever.

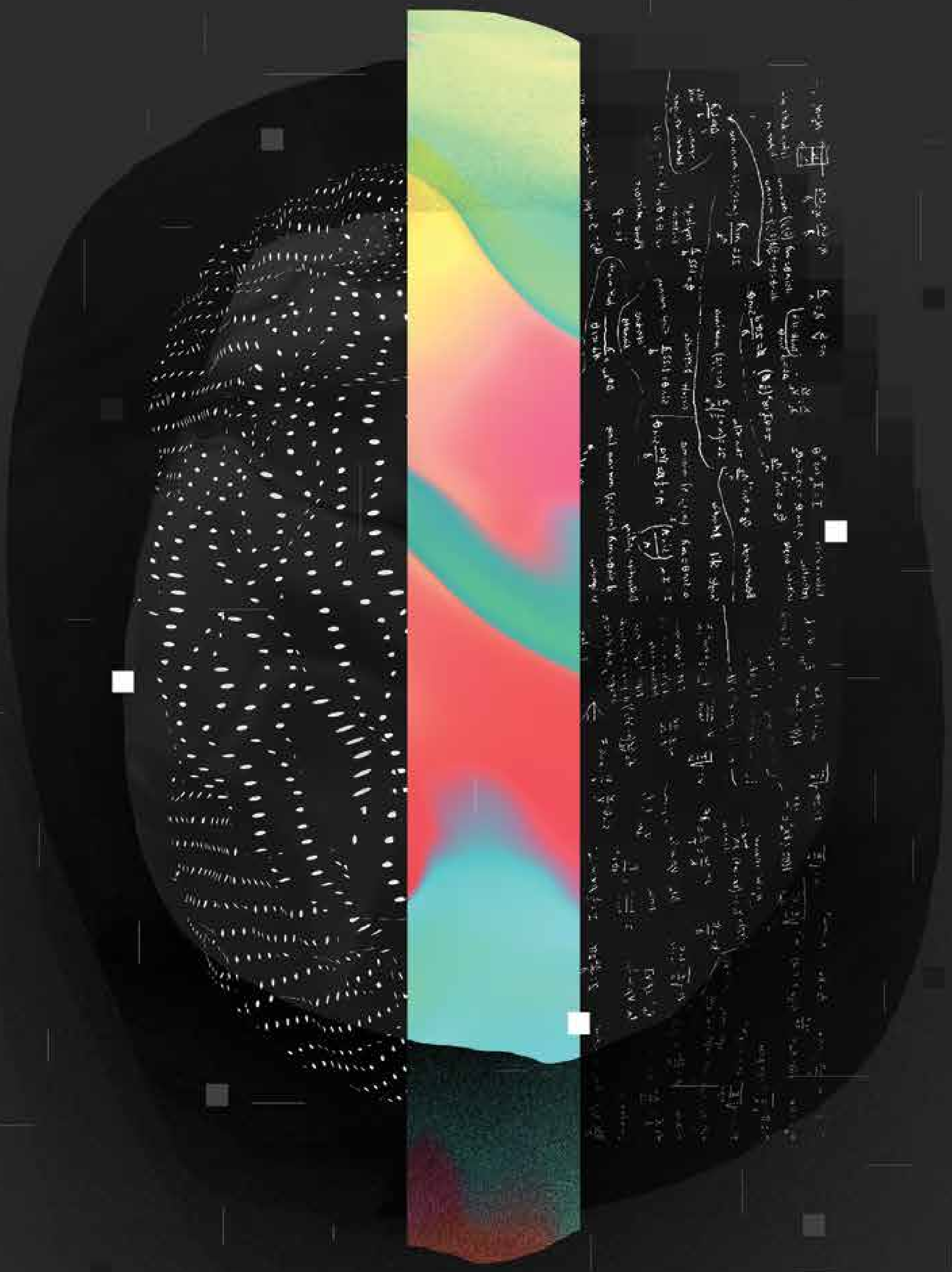
The Tough Tech founders we work with have already taken the first leap to commercialization—they have done the hardest work, the imagination, and the innovation.  It’s our job to help them navigate this nuanced and intimidating landscape by providing them with entrepreneurial knowledge, expertise, inspiration and technical tools, as well as the space flourish. We believe that the challenges inherent in commercialization are a necessary catalyst for novel thinking, and that the journey out of the lab is an important one.

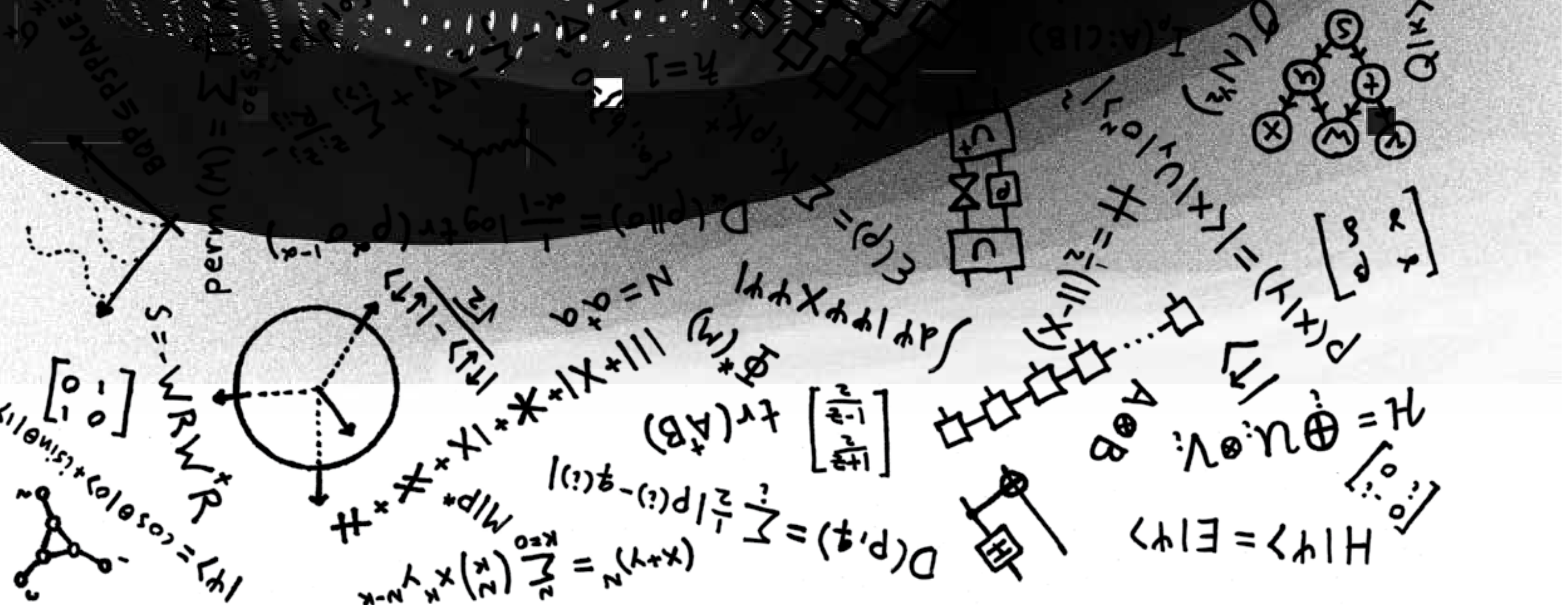
The transformative ideas featured here are far from exhausting their potential. And as the commercial viability of quantum computing and fusion energy edge closer, we can expect to see breakthroughs accelerate, spurred forward by an alchemy of science and business.

# The Future is QUANTUM

*Quantum computing could revolutionize computing as we know it—if engineers can figure out how to make it useful.*

By *Michael Blanding* for *The Engine* | Illustration by *Vasjen* | Portraits by *Danilo Agutoli*





**Will D. Oliver**
Physics Professor of the Practice and Associate Director of the RLE (MIT), and Lincoln Laboratory Fellow

**Christopher Savoie**
CEO, Zapata Computing

**Peter Love**
Associate Professor of Physics and Astronomy, Tufts University

“Do you want to see the computer?” physics professor of the practice Will Oliver asks, sitting in his office on the third floor of Massachusetts Institute of Technology’s Building 13. As he leads the way down the concrete stairwell to the ground floor and down the hallway, a pulsing whir gets steadily louder. “We have to keep the team up here—otherwise it would be too loud for them to work,” he says, opening the door to the lab, where several grad students sit hunched over computer monitors.

Stacks of shiny chrome boxes fill one wall covered in knobs, buttons, and colored wires like the world’s most elaborate DJ system. Several of them sport their own monitors showing oscillating waves in Technicolor turquoise and magenta. It looks less like a modern computer than a mainframe from a half-century ago. Technically, however, this isn’t the computer that Oliver has come to show off. That is another level down, connected to this control system through the floor and suspended in several super-cooled refrigerators.

“That pulsing sound you hear is cooling the temperature down to about outer space,” says Oliver, nonchalantly, as he leads the way downstairs. That temperature, some 2.7 Kelvin or -270 Celsius, is only the first stage in cooling the computer down to the temperature it really needs to operate. “It’s shielded like a series of Russian dolls,” Oliver says, pointing out four refrigerators suspended from the ceiling. The outer layer of each looks like nothing so much as a white plastic trash barrel. Through each layer, the devices gets successively colder, until they reach 20 Millikelvin. “So we are about 100 times colder than outer space,” says Oliver. “That’s where the qubits live.”

Qubits are short for “quantum bits”—the heart of this strange contraption, called a quantum computer, that may just transform our conception of what computing can be. Ever since the invention of the first computers, engineers have pushed to make them faster. Starting with vacuum tubes of ENIAC and progressing through the invention of transistors and the silicon microchip, computers have progressed with blinding speed over the last half-century to the point where today’s supercomputers can perform more than a thousand million million operations a second.

A funny thing has happened over the last decade or so, however. Even as computers have continued to get faster, the speed of that increase has been slowing down. For 50 years, silicon chips have followed Moore’s Law, named after Intel founder Gordon Moore, which held that the number of transistors you can fit on a microchip would double every two years. In 2016, Intel acknowledged the inevitable—that there only so many transistors you can cram onto a chip, and updated its rate of doubling to every five years.

Intel shouldn’t feel too bad, however. No matter how fast silicon-based computers get, some problems are literally just too difficult for them to solve. A simple chemical reaction, for example, might involve 30 or 40 electrons. Keeping track of all of their positions and states requires an exponential number of calculations that quickly taxes the capabilities of even the fastest supercomputer. “If you used every bit of silicon in the universe, you would still not be able to solve these problems,” says Christopher Savoie, CEO of quantum computing company Zapata.

That’s where quantum computers come in. Suspended in their deep freeze inside a lattice of copper struts and wires, qubits operate on the principle of quantum mechanics, making them capable of performing feats beyond the reach of any silicon-based computer. That makes a quantum computer as different from a classical computer as a string of 1s and 0s differs from the complexity of an atom. Since they were first proposed some 40 years ago, physicists and computer engineers like Oliver have worked to harness that complexity with an actual working quantum computer.

Now, those engineers stand on the cusp of demonstrating the Holy Grail: a quantum computer that can conduct a calculation that is impossible to simulate on a classical computer. Companies including IBM, Google, Microsoft, and Intel—as well as several smaller startups—are all racing to be first to achieve that feat, dubbed “quantum supremacy,” which will almost certainly happen in the next year or two. That moment, however, is only the first step in the possible quantum computing revolution to come, the high-tech equivalent of a bar bet. Beyond all of the hype and science fiction of unleashing a dramatically new form of computing into the world, the question remains: what can quantum computing do that is actually useful for the world?

Words quickly fall away when trying to explain what a quantum computer actually does, with explanations sounding in short order like—take your pick—alchemy, voodoo, magic. “You lose something when you go from classical to quantum,” says Tufts University quantum theorist Peter Love. “That is, a picture of science in which you make measurements to uncover a pre-existing reality that was there before you measured it. You can’t think like that. Quantum measurement is participatory.”

Put another way, classical computing can be reduced to series of bits, essentially containers that contain either a 0 or a 1 at any given time. “You can reproduce every action of a classical computer by writing numbers on a piece of paper,” says Love. “There’s no difference there between an ENIAC and a modern laptop.” A quantum bit, on the other hand, represents a process, which could either be a 0 or a 1, but doesn’t actually decide which until the moment you measure it. That state, called a superposition, is at the heart of quantum mechanics—the famous Schrödinger’s cat that can be alive and dead at the same time.

*No matter how fast silicon-based computers get, some problems are literally just too difficult for them to solve.*

“If you want to represent the state of a quantum computer, well now you are in a bit of a pickle,” says Love. The best that someone could do, he continues, is to write down the probability of whether each qubit would be a 0 or 1 at any particular moment of measurement—a mammoth undertaking. “If you have n qubits, you would need 2 to the n possible measurements,” says Love. Ten qubits would yield over 1,000 possibilities; twenty would yield over a million. “That’s a huge number of pieces of paper,” Love says.

Furthermore, qubits can be “entangled” with one another, meaning that the state of one (0 or 1) is related to the state of another. “If I’m not able to describe the state of qubit one independently of qubit two, that’s entanglement,” Love says. Those two qualities, superposition and entanglement, may seem esoteric. Practically speaking, however, they mean that quantum computers can take shortcuts in calculations, wiping out the laborious process of clicking through calculations one by one, to arrive at a solution to a problem much more quickly and with much less effort.

The idea of creating a quantum computer was first proposed by theoretical physicist Richard Feynman, in a lecture, “Simulating Physics with Computers,” that he gave in 1981.(1) In it, he provocatively asked whether it was even possible to truly simulate physics with classical computers. Since the true nature of physics is quantum mechanical, he said, the closest a classical computer could ever get to truly simulating the universe is only an approximation. “And I’m not happy with all the analyses that go with just the classical theory, because nature isn’t classical, dammit,” he concluded, “and if you want to make a simulation of nature, you’d better make it quantum mechanical, and by golly it’s a wonderful

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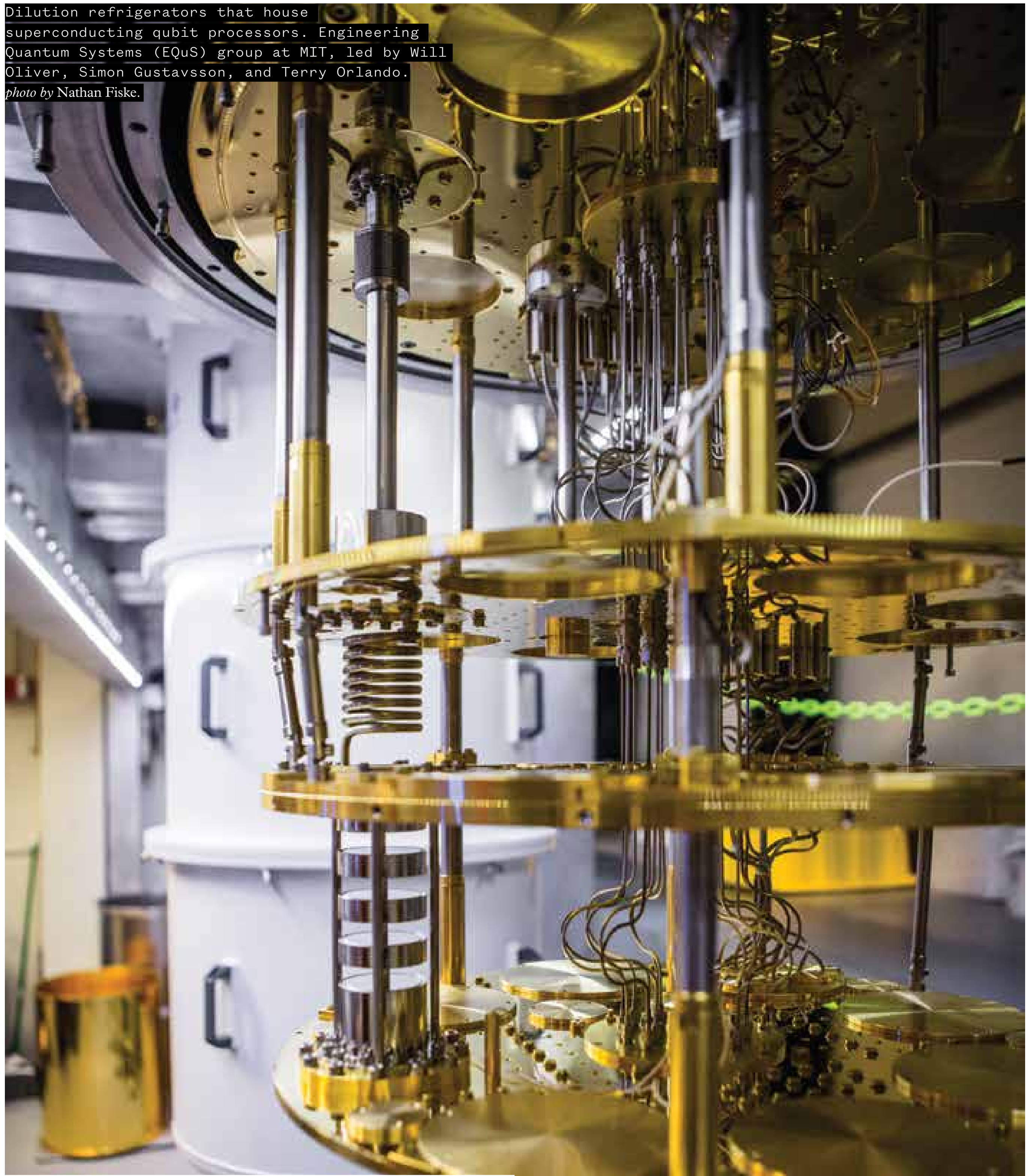
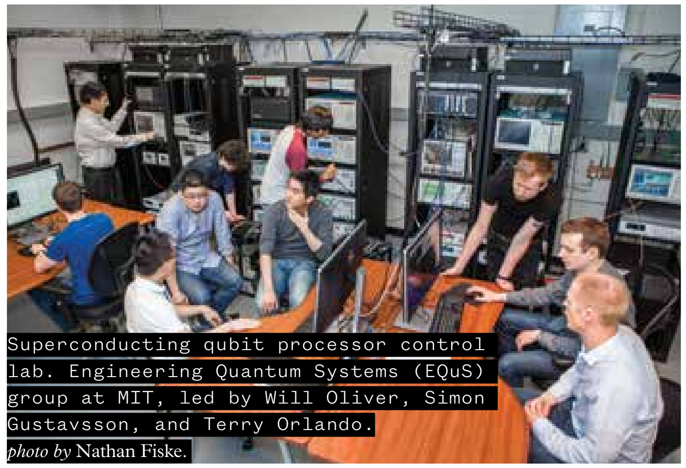
(1) http://physics.whu.edu.cn/en/sites/physics.whu.edu.cn.en/files/1_00_QIC_Feynman.pdf



Dilution refrigerators that house superconducting qubit processors. Engineering Quantum Systems (EQuS) group at MIT, led by Will Oliver, Simon Gustavsson, and Terry Orlando.
*photo by* Nathan Fiske.



Superconducting qubit processor control lab. Engineering Quantum Systems (EQuS) group at MIT, led by Will Oliver, Simon Gustavsson, and Terry Orlando.
*photo by* Nathan Fiske.

problem, because it doesn't look so easy."

The first computers, such as ENIAC and UNIVAC, were created to simulate the trajectory of artillery fire for the US military, using differential equations to approximate the outcome. Over the years, computers have been able to do different tricks in different fields to approximate results in other fields, ranging from particle physics to superconductivity. "For most systems, a classical approximation is good enough," says Aaron VanDevender, a quantum physicist turned venture capitalist with the Founders Fund. "But we have reached a limit, and it's a bit of a lie we are telling ourselves that the universe is classical and it's okay to run these simulations on a classical computer." The power of a quantum computer is that it could theoretically yield not just approximate results, but precise results in a common language without the specialized tricks for each field. "You can use one quantum system to simulate any other quantum system," VanDevender says. "From a battery to a black hole."

> ***The power of a quantum computer is that it could theoretically yield not just approximate results, but precise results in a common language without the specialized tricks for each field.***

That could have applications in a wide range of areas. In a 2005 paper in *Science,* for example, Love and Harvard's Alán Aspuru-Guzik suggested that just a few dozen qubits could be used to simulate the molecular energies in many chemical processes better than classical computers ever could.(2) From there, it's a quick leap, says VanDevender, to imagining how quantum computers could help speed development of a wide array of chemical and biological products. "Looking at how biological molecules interact with each other, or bind to each other in a cell, or how an enzyme catalyzes a reaction, or the energetics of a drug moving through a membrane—these are all quantum mechanical reactions," VanDevender says. Developing algorithms to simulate these interactions could aid in high-throughput drug screening, enabling exact simulation of millions of compounds in the virtual realm before honing in on a handful to test in the lab.

Quantum computing could have applications in other areas as well—for example, finding the optimal route for package delivery or a ride-sharing service. It could also help make machine learning and searching more efficient. In 1996, for example, Bell Labs computer scientist Lov Grover proposed a quantum algorithm that could rapidly improve database searches. "Say you had four playing cards face-down, and one of them is a queen," explains Zapata's Savoie. "In a classical search, you'd need to turn over all of the cards, so mathematically, you'd need to turn over an average of 2.25 cards before you find the queen." With Grover's algorithm, however, a computer could simulate the four cards using two qubits, having all four states available to it at once. "The analogy would be that you peek under all four cards at the same time, so you are guaranteed to get the answer in one shot every single time," says Savoie. Magic.

Somewhat more sinisterly, quantum computing could also totally subvert the field of modern cryptography. The most common standard of cryptography that protects all of our passwords and credit-card purchases online—to say nothing of sensitive national security communications—is predicated on the assumption that it's practically impossible for computers to determine the prime factors of extremely large numbers. A quantum algorithm created by MIT mathematician Peter Shor in 1994, however, could theoretically attain that feat with a relatively small number of qubits. "If you can build this quantum computer, that upends all of modern cryptographic communication systems," says VanDevender. "If you're the NSA, that's an existential threat to the system."

The intelligence community doesn't have to worry about such threats yet, however. Since quantum physicists began working in earnest to try and create a quantum computer in the late 1990s, they have yet to build anything approaching a working machine, never mind running anything as complex as Grover's or Shor's algorithms at scale. That's due to one simple reason: to create an effective quantum computer, it's necessary to isolate qubits from the outside environment enough so that interactions with the outside world don't create errors, a concept known as coherence. At the same time, they have to be sufficiently connected to the environment that they can be manipulated into performing the operations required of them. That combination has proven extremely difficult, especially as engineers have tried to scale up from two qubits to 5 or 10 or 100.

"Even five or six years ago, it wasn't clear we'd ever be able to make a useable

***Aaron VanDevender***
Chief Scientist and Principal,
Founders Fund

***Alán Aspuru-Guzik***
Professor of Chemistry and Chemical
Biology at Harvard University,
Chief Scientific Officer,
Zapata Computing

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(2) http://science.sciencemag.org.resources.library.brandeis.edu/content/309/5741/1704

**Peter Johnson**
Quantum information scientist,
co-founder Zapata Computing

**Robert Schoelkopf**
Sterling Professor of Applied
Physics and Physics, Yale
University. Chief Architect &
Co-Founder, Quantum Circuits

system," says Robert Schoelkopf, a Yale physicist who has been experimenting to create quantum computers since 1998. "In the beginning, the question was if we would ever be able to make a qubit well enough and isolated from the environment enough that we could have superconductors that we could manipulate with some reasonable fidelity."

Currently, two leading contenders for quantum computing technology are superconducting circuits and trapped ions, both of which have their benefits and drawbacks. Superconducting circuit qubits, like those in Oliver's lab at MIT, use the same basic techniques as those used to create modern computer chips, using semiconductor manufacturing tools to deposit, pattern, and etch superconducting aluminum on silicon wafers. For the qubit, two layers of superconducting aluminum are separated by a layer of insulating aluminum oxide; through that, a tiny tunnel called a "Josephson junction" allows millions of electron pairs to flow without resistance, creating quantum states and discrete energy levels just like a giant atom.

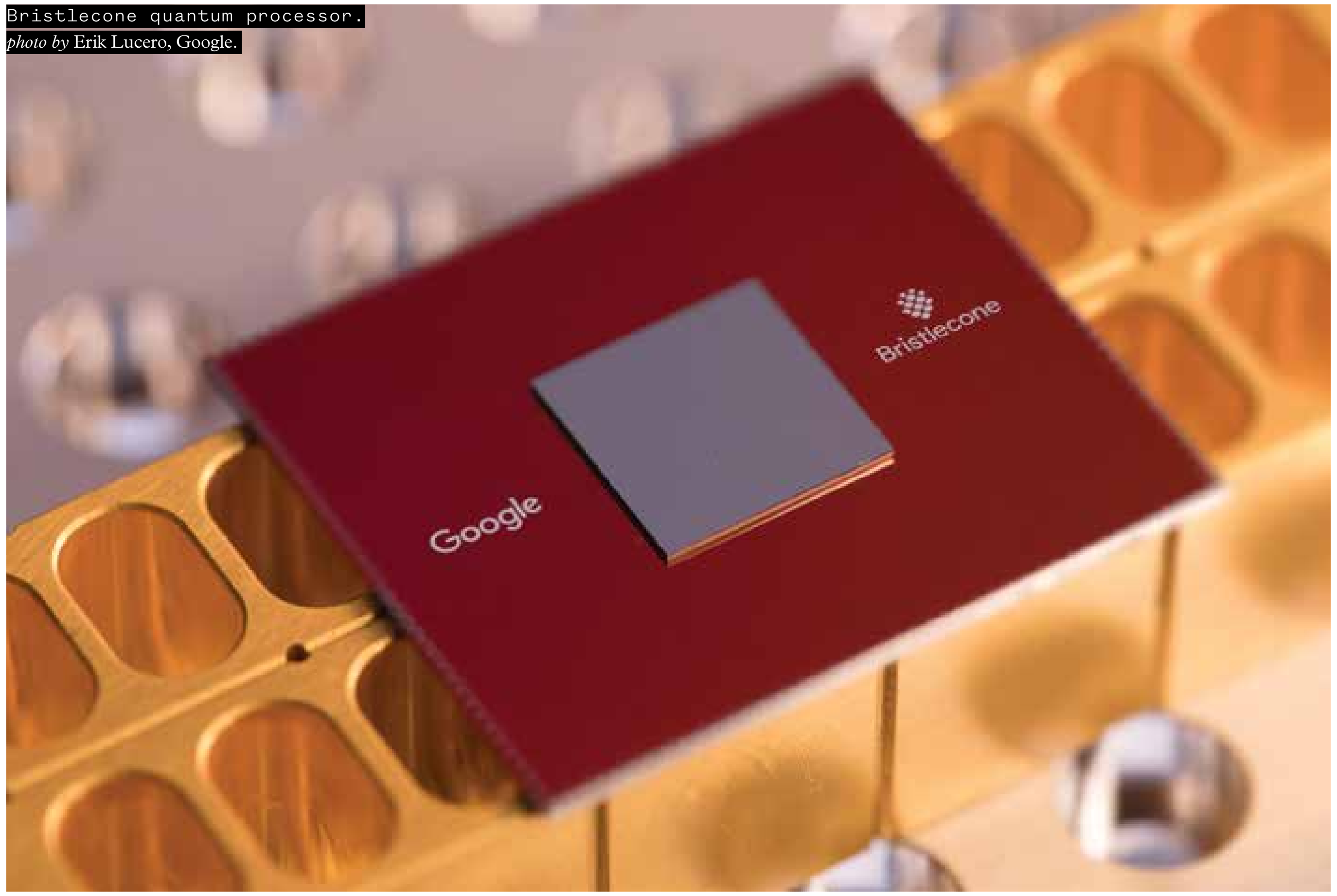
By cooling the qubit down to extremely low temperatures, engineers can control the frequencies at which this state resonates to create two phases, which then become the 0 and 1. By hitting the qubit with a microwave pulse, they can drive the transition from one state to another, or leave it in superposition between them. The problem is that, thus far, the circuits can only remain in superposition for relatively small periods of time—currently around 100 microseconds. "We want to make that lifetime as long as possible compared to how long it takes to drive from ground to excited states," says Oliver. "The question is, how many of these gates can I perform before I lose that quantum information?" Current times are still long enough to perform 1,000 to 10,000 gates depending on the complexity of the operation, a tremendous improvement over the past 15 years, but not yet long enough to do anything useful.

The other leading form of qubits today are trapped ions, which consist of charged particles suspended in vacuum with an electromagnetic field, and hit with pulses from lasers to drive their different states. Compared to superconducting qubits, trapped ions are able to maintain their coherence longer—up to a leisurely second or longer —but they are also much slower to respond to pulses from the outside environment, so the total number of gates possible with both technologies is about the same.

Superconducting qubits and trapped ions have other differences as well. With trapped ions, for example, it's possible to entangle any qubit with any other in the same trap. With superconducting qubits, however, qubits must each be discretely connected to each other in order to allow entanglement—so in linear architecture, for example, each qubit could only be entangled with its immediate neighbor, while in a square lattice, each could be connected perpendicularly or diagonally with multiple other qubits. Oliver's lab has been further experimenting with a three-dimensional architecture that could create connections between qubits that are not immediately adjacent.

Behind those technologies are a number of other techniques for creating qubits that may one day show promise or even exceed the abilities of superconductors and trapped ions. After all, as MIT physicist Seth Lloyd once said, since the natural state of the world is quantum, "Almost anything becomes a quantum computer if you shine the right kind of light on it." So far, other contenders include: *neutral atoms*, single atoms suspended in a lattice that can be hit by lasers to excite them to a quantum state without affecting nearby atoms; *photons*, quanta of light emitted by atoms that can be redirected to interact with themselves with mirrors; *quantum dots*, consisting of "puddles" of electrons on the nanoscale, each with its own quantum spin; and *nitrogen-vacancy centers* in diamond, which exploit natural imperfections in diamonds that create free-floating spare electrons that can be manipulated into a quantum state.(3,4,5,6,7) Another dark horse technology is *topological qubits*, theorized by Alexei Kitaev at Caltech, which depend on a theoretical quasiparticle called a Majorana fermion. The advantage of these qubits is that they are theoretically much more stable than other kinds; the disadvantage is that to date, no one has successfully demonstrated that such particles exist.

Each of these technologies has its own advantages and disadvantages—some are faster, for example, while others are less error-prone, though none of them are ideal so far. "These days, it's hard to pick a winner," says Savoie. "You know, which horse do you want? Well, that one's slow and gimpy, but this one's got a sore on its heel. They are all kind of bad." No matter what technology is used, creating a functional quantum computer requires simultaneously making qubits faster and protecting them from the errors that can cause decoherence in order to maintain their superposition states longer. Errors



Bristlecone quantum processor.
*photo by* Erik Lucero, Google.

can result from two sources: control errors and decoherence. A control error is analogous to setting the radio dial slightly off from a station, creating a bit of static. With superconducting qubits, for example, each one will be slightly different than the others, and they must be carefully calibrated in order to respond to the microwave pulses that control their gates.

Decoherence errors are a bit more insidious—the same entanglement that allows qubits to connect with one another can backfire when they become entangled with other atoms in the environment instead. "There is something that's called the monogamy of entanglement," says Peter Johnson, a quantum theorist at Harvard who is also part of the founding team of Zapata. "If I am wed to you, I can't be wed to someone else." In order to protect against promiscuity, quantum engineers follow one of two methods. Passive error suppression consists of sending small pulses to dynamically decouple qubits from the environment. Oliver likens it to the way lacrosse players cradle the ball in the stick pocket, moving it rhythmically back and forth as they run down the field. "If you just held the stick, the ball would fall out," he says. "By making these body motions periodically, it will stay in longer."

Active error correction, meanwhile, focuses on flooding the zone with so many qubits that they will together compensate for decoherence in any small number of them. "You are kind of hiding the information from the environment," says Johnson, who poses the following analogy: "Say I wanted to tell you whether the Celtics won last night, and I am going to do this by handing you a penny that is either heads or tails. But there is a 10 percent chance of the coin being flipped." One way to protect against that problem would be to send three pennies instead of one—so even if one penny came out tails, you could still be relatively sure from the two heads that Boston won the game. Extrapolated out beyond three pennies, it's easy to see how each additional penny you received would increase your confidence until you got to the point where you absolutely certain of the outcome. Unfortunately, achieving that kind of error correction with a 100-qubit computer would require on the order of 100,000 or a million qubits just to keep errors in check. "That gets costly very quickly," says Johnson. "A million pennies is $10,000." Of course, when talking about qubits rather than pennies, that cost gets astronomically larger.

In the short term, most companies working towards creating a quantum computer are focusing just on putting enough qubits together into a single device in order to actually do simple computations. Due to the substantial costs of fabrication, companies have had to choose one technology. By far, the most popular is superconducting qubits, which is the method of choice for IBM, Google, and Intel, who can leverage their existing expertise in lithographic tools for silicon

> ***As MIT physicist Seth Lloyd once said, since the natural state of the world is quantum, "Almost anything becomes a quantum computer if you shine the right kind of light on it."***

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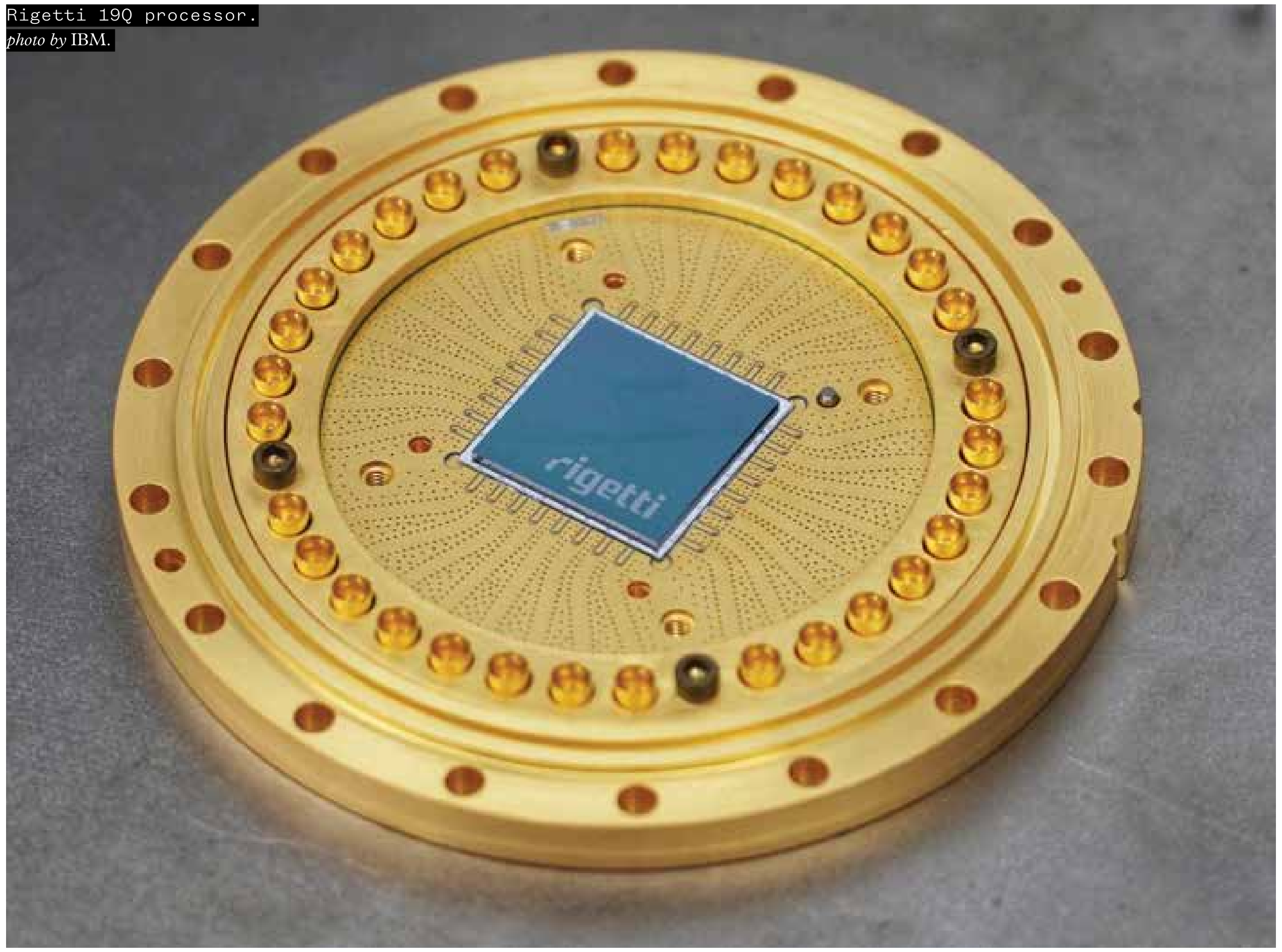
(3) https://www.sciencedaily.com/releases/2015/08/150812151247.htm
(4) https://scitechdaily.com/new-kind-quantum-computer/
(5) https://news.stanford.edu/2017/05/09/new-materials-bring-quantum-computing-closer-reality/
(6) http://news.mit.edu/2017/toward-mass-producible-quantum-computers-0526
(7) https://quantumfrontiers.com/2017/08/16/topological-qubits-arriving-in-2018/

IBM Q Experience.
*photo by* IBM.



Rigetti 19Q processor.
*photo by* IBM.

in a new superconducting medium. Several startups are also experimenting with superconducting qubits, including Rigetti Computing, based in Berkeley, California, and Quantum Circuits, spun out of Schoelkopf's Yale lab. Maryland-based startup IonQ, meanwhile, is pursuing a trapped ion approach, while Microsoft has placed a bet on topological qubits.

All of these companies are engaged in a race to see who can put the most qubits together into a functioning chip in order to be the first to achieve the quantum supremacy moment that can demonstrate a quantum computer that can best its classical cousins. At the present moment, Google is leading that race with the announcement in March of a 72-qubit processor it dubbed Bristlecone after the prickly distribution of x-shaped qubits in its square array.(8) In its announcement of the technology, Google said that it believed that it could use a processor of this size to demonstrate quantum supremacy.

Of course, that feat requires performing calculations with a low enough degree of errors. “The critical piece is not just the number of qubits, it's also the fidelity of the system,” says Google researcher Sergio Boixo, a former physics professor at the University of Southern California. While Google hasn't released the error rates for its current chip, past chips have had rates as low as 0.6 percent for 2-qubit gates, a critical measure of fidelity. Boixo notes that Google has focused its efforts on increasing the number of qubits while maintaining the current rates of fidelity, and eventually even increasing gate fidelity. The company estimates that it will need error rates of less than 0.5 for 2-qubit gates to achieve quantum supremacy, and recently updated its timeline to predict it would achieve that supremacy sometime this year. IBM and Intel are not far behind, unveiling 50-qubit and 49-qubit chips, respectively, at January's Consumer Electronics Show in Las Vegas. With a low enough error rate, those chips could also achieve quantum supremacy in the near term.

***Sergio Boixo***
Research Scientist and Theory Team
Lead of Quantum AI, Google

The best way for a quantum computer to demonstrate supremacy, of course, would be to model a quantum system. Even the most basic chemical reactions, however, are beyond the scope of the noisy non-error corrected devices any of the companies will be able to produce in the near future. In a paper published in April in *Nature Physics*, Boixo proposed that the one way to demonstrate quantum supremacy would be to calculate the outcome of a sampling of random quantum circuits—a task notoriously difficult for classical computers to achieve.(9)

*“I want to revolutionize history though computing.” - Alán Aspuru-Guzik*

Such a task, while certainly a milestone, would be a far cry from a universal quantum computer that could run useful algorithms such as Grover's and Shor's algorithms or simulate quantum systems for use in chemistry and biology. For that reason, many quantum researchers have moved away from using the term “quantum supremacy” as the indicator for achieving success in the field. Even Caltech physicist John Preskill, who first coined the term quantum supremacy in 2011 has tried to downplay the hype, writing in a paper published in January that “quantum supremacy is a worthy goal, notable for entrepreneurs and investors not so much because of its intrinsic importance, but rather as a sign of progress towards more valuable applications further down the road.”(10) In his paper, Preskill proposed a new-term, NISQ or “noisy intermediate stage quantum” to define the stage in which systems with 50 to 100 qubits might still be able to perform useful tasks better than classical computers, even without error correction.

That's been the focus of chemistry professor Alán Aspuru-Guzik, who is currently at Harvard but moving to the University of Toronto this summer. His office is full of Shepard Fairey graphic prints of revolutionaries in red and black. “I like these images of these heroes doing something for humanity,” he says. “I want to revolutionize history though computing.” After watching his postdocs and graduate students leave one by one for the likes of Google and Intel, he decided to start his own quantum computing company last summer, sketching out the company “over a couple of burritos at the Qdoba in Harvard Square.” After casting around for a sufficiently revolutionary name, he settled on Zapata, after Emiliano Zapata, the peasant leader during the Mexican revolution. “He was a good guy, and he had a beautiful moustache,” he says.

Unlike most quantum companies, which have focused on building quantum computing hardware, Zapata has focused on what might be considered software—the algorithms that drive quantum computing calculations. Before creation of a universal error-corrected quantum computer powerful enough to run algorithms like Grover's and Shor's, Aspuru-Guzik says, there will be a long period in which they can still run useful programs. “We already know the algorithms for a million qubits,” he says. “My company's job is to figure out what are the algorithms for these decades of 100, 1,000, and 10,000 qubits.” Zapata is looking past the point of quantum supremacy—which Aspuru-Guzik prefers to call “quantum inflection point because the word supremacy is loaded politically”— to how quantum

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(8) https://ai.googleblog.com/2018/03/a-preview-of-bristlecone-googles-new.html
(9) https://www.nature.com/articles/s41567-018-0124-x
(10) https://arxiv.org/pdf/1801.00862.pdf

Rigetti Lab in Berkeley.
*photo by* Rigetti.

*The real race may not be between quantum and classical computers, after all, but between quantum hardware and quantum software.*

***Jerry Chow***
Manager of Experimental Quantum Computing, IBM

***Chad Rigetti***
Founder and CEO, Rigetti Computing

computing can best classical computing in the NISQ era. “The interesting point is what happens between 200 and a million qubits. What's the first point that it will do a quantum task that is useful for humanity?”

Ultimately, Zapata aims to focus on chemistry, which Aspuru-Guzik and Peter Love identified more than a decade ago as the ultimate quantum problem, helping to design algorithms that might better identify catalysts for chemical processes or candidate molecules and materials. In the meantime, however, he says quantum algorithms will be able to aid in any problem that will require a more optimal answer, even if it can't ultimately provide the best answer. Those problems could include machine learning, compression, route optimization, and searching. He calls such algorithms “variational algorithms” and compares them to tuning a guitar string with the help of a tuning fork. “The tuner is what I want the quantum algorithm to do, but I can use the algorithm to get the strings of a chord closer to the notes I want,” he says.

Zapata's CEO Christopher Savoie compares this stage in quantum software development to the early years of classical computing, even before the invention of assembly language, never mind modern computer languages like C. At this point, the company is literally sketching out its algorithms as complex circuits, and sending those to companies it partners with in order to perform certain tasks. “So the program software is a soft piece of paper for now,” he quips. So far, Savoie estimates, Zapata has been involved in a large majority of the near-term algorithms currently being tested on quantum computers, partnering with all of the major companies to run algorithms on their systems. Being flexible on which technology it uses allows Zapata to pick the ideal configuration of qubits able to be entangled with each other in order to pull it off. “We might go to a customer like a pharmaceutical company, and they say, here's the mathematical problem we're trying to solve,” he says, “and we take that and draw a bunch of Greek letters on the board, and then convert that into a diagram. Then we might say, oh wow, I need linear connectivity for this thing—or I need a lot of samples, so I need faster gate speeds, and we'll make that choice.”

In various ways, other companies are developing their own approaches for making quantum computing useful in the near term. Schoelkopf, who created his own company Quantum Circuits out of his lab at Yale, is pursuing a strategy of integrating both hardware and software in one package. “We plan to field the first useful quantum computing systems,” he says. “It's likely this will be offered as a service, since these things aren't very portable for now.” His lab has been pursuing a unique modular architecture, which would put qubits on smaller chips that could be networked into a system in different configurations depending on what type of problem a client is trying to solve. “It means you could probably be more efficient in implementing certain algorithms, because you are not stuck to one network of connectivity,” he says.

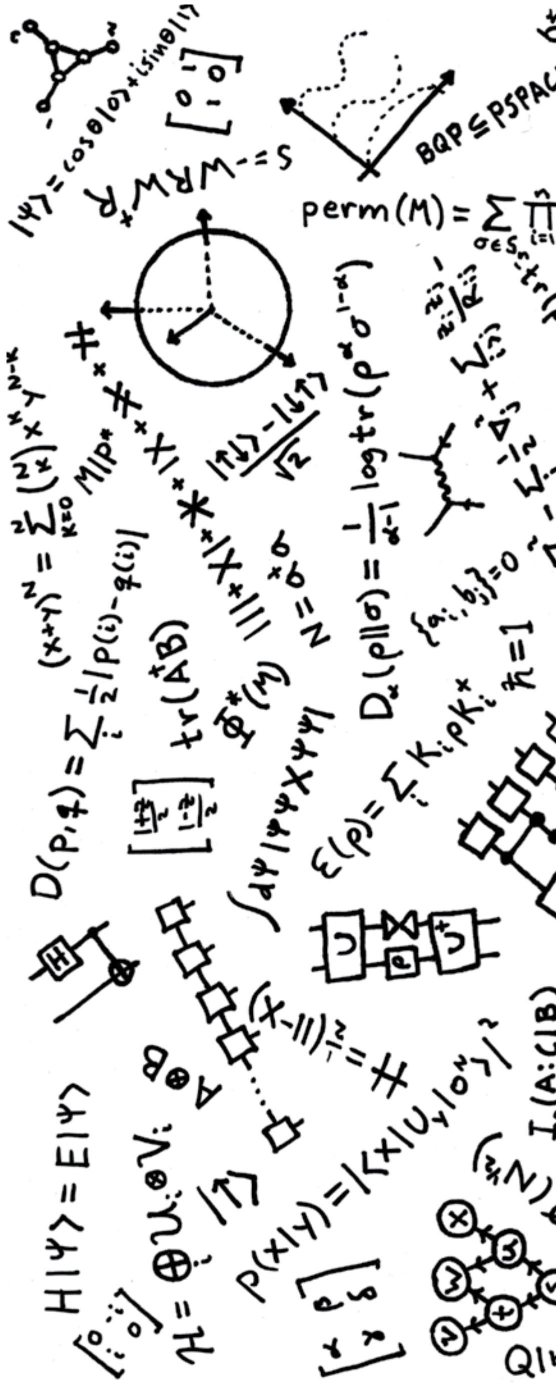
In addition to its own success in fabricating quantum chips, IBM has focused efforts on educating the public on the potential of quantum computers, to prepare them for the eventual moment when they will be able to perform useful functions. Recently, it launched the Q Experience, a cloud-based interface in which users can use a quantum composer, which looks like an image of guitar tablature to drag-and-drop gates onto qubits to perform algorithms on real quantum computing hardware.(11) “It allows us to reach a broader community of students, researchers, and just people who are interested in learning about new computing technology,” says Jerry Chow, IBM's manager of experimental quantum computing. “The idea is to break down barriers, so you are not the only person at the cocktail party who understands what quantum computing is.”

IBM's website also features video tutorials by its engineers breaking down quantum computing concepts into bite-sized 3-minute lessons to demystify the field. “We call that getting ‘quantum ready,’” Chow says. Already, the company has gotten a lot of interest from college and even high school students eager to learn about the new technology. For more advanced users, IBM has begun to develop its own programming language for quantum computing called QISKit, an open-source software which uses Python scripts to execute algorithms on quantum hardware.(12) “One of the most important things we can do in the near term is get more people involved,” Chow says. “It's really tapping into the developer mindset, where we want to cultivate the next generation of quantum developers.”

Berkeley-based start-up Rigetti has been building it own “soup-to-nuts” quantum company from the ground up, including building chips, computer, and software at the same time. The company has focused on speed, building a quantum integrated circuit fabrication lab that can iterate a new design on a 4-6 week timeline, rather than the 12-18 month timeline that might be typical to build a new quantum chip. “Since we first started manufacturing chips in January 2016, we've doubled the number of qubits every six months, and we expect to keep doubling every six months for a handful of years,” says CEO Chad Rigetti. Currently, Rigetti's biggest publicly released chip has 19 qubits—though he says they already have a doubling or two beyond that (though the company has not released exactly how many yet).

Like IBM, Rigetti has created its own cloud-based programming interface, which is calls Forest, a similarly open-source software using Python scripts. Rather than focus solely on the quantum environment, however, Rigetti's language allows for the integration of quantum and classical computers in the same program, something the company calls “quantum-classical hybrid computing.” “It uses a quantum computer as part of an optimization loop on a classical machine,” Rigetti explains. Rather than quantum supremacy, he likes to use the term “quantum advantage” to explain how, in the near-term at least, quantum computing can help to improve solutions to problems by providing an answer that is more efficient, or takes less time, or costs less money, than a classical computer can do alone.

Until engineers can truly build a quantum computer that is free enough from errors to perform the advanced calculations, this may be the future—a convergence of increasingly better quantum computers and increasingly better algorithms to perform more and more useful tasks. The real race may not be between quantum and classical computers, after all, but between quantum hardware and quantum software. “Quantum chips are going to continue to improve at an exponential rate, and pretty soon the physical capability is going to outstrip what we know how to take advantage of,” Rigetti says. “There will be huge value in capturing the right algorithms to unlock these possibilities.”+



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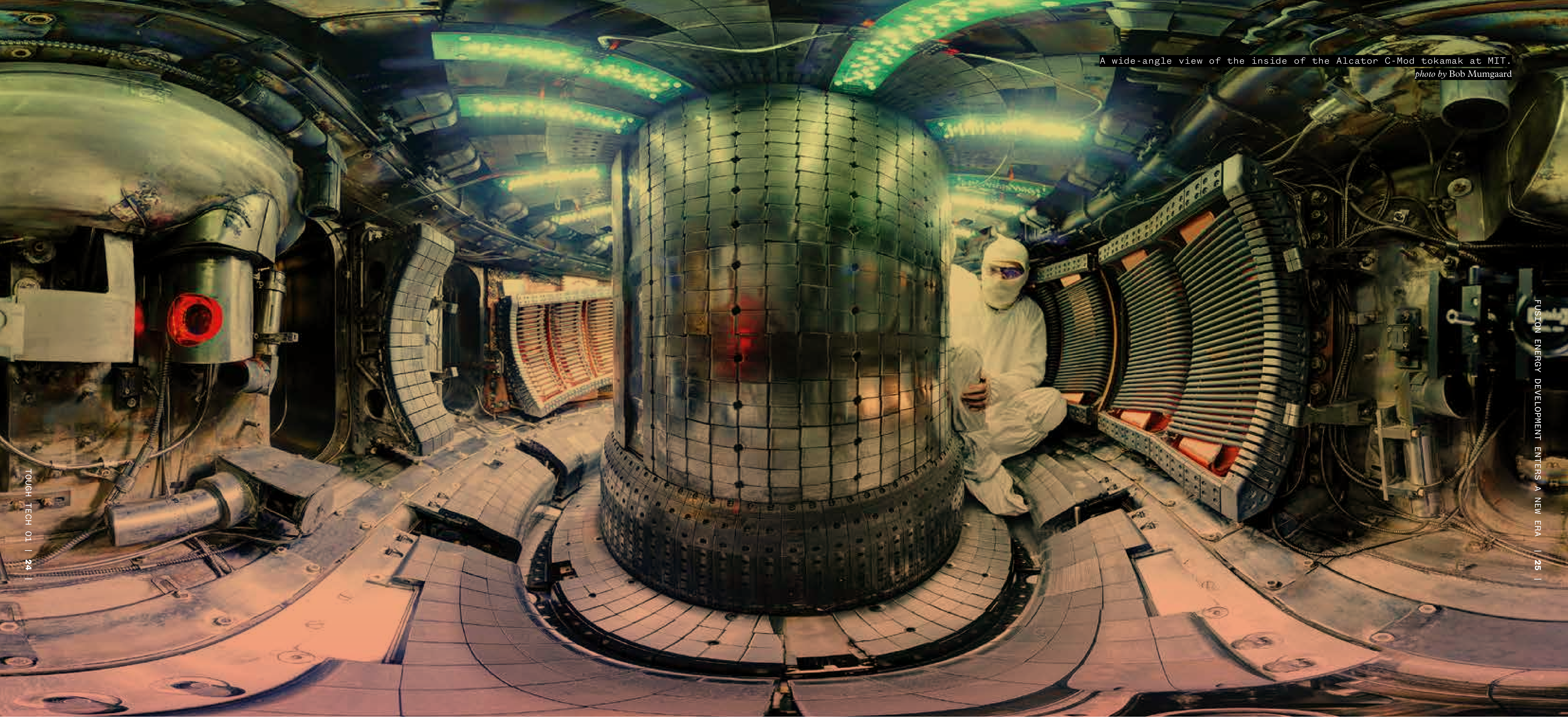
(11) https://quantumexperience.ng.bluemix.net/qx/experience
(12) https://qiskit.org/



A wide-angle view of the inside of the Alcator C-Mod tokamak at MIT.
*photo by* Bob Mumgaard

Knowledge, capital, and a growing sense of mission:

# FUSION ENERGY DEVELOPMENT

# *Enters a New Era*

By *Peter Dunn, for The Engine* | Illustrations by *Julie Carles*

*Can today's group of fusion startups demonstrate net-positive, commercially-viable fusion in time to make a difference? Or should their work just stay in the lab?*

The prospect of plentiful, inexpensive, carbon-free electricity generated by fusion has been tantalizing but elusive since the 1950s. Despite painstaking, groundbreaking science-oriented research at academic and government research labs, no one has yet achieved a net-positive fusion reaction that produces more power than it consumes.

But a new dynamic and new optimism are afoot in the fusion community, as evidenced by increasingly vibrant private sector activity. Roughly 20 fusion companies are now in operation, backed by some $1 billion in capital and with seven decades' worth of hard-won knowledge to draw on. The most recent of those is Commonwealth Fusion Systems (CFS), which spun out of MIT this year and is supported by The Engine.

Each company is pursuing a distinct strategy towards the sequential goals of demonstrating net-positive fusion and applying it in a practical power plant, drawing on its own expertise and new advances in areas like magnetics, materials, and control systems. And several have announced roadmaps for demonstrating of energy-gain fusion by the mid-2020s and usable reactor designs in the early 2030s, with commercial availability shortly thereafter.

That unprecedented assertiveness comes not only from greater knowledge and the increased risk tolerance of private organizations, but also from an increasingly imperative sense of purpose. There's a widespread perception among fusion-oriented scientists, engineers, managers, and investors that they have the opportunity—and, indeed, the duty—to address grand problems facing the entire planet.

"It's more than just electricity. It's food, water, health, living standards. If we don't make a course correction in the next 25 or 30 years, humanity will not be in a good spot; it's a moral obligation to our kids, and fusion is like a 'get out of jail free' card," says Michl Binderbauer, president and chief technology officer of TAE Technologies, which after 20 years in business is one of the longest-standing fusion companies. "We're seeing this sense of urgency and passion in everyone who works for us, and especially the younger people."

## "Leveraging the Power of the Stars"

For all its world-changing potential, fusion must still pass a basic test: proving its worth as a means of generating electricity against competitors like natural gas, solar, wind, geothermal, hydro, and new-generation nuclear fission (some of which can be augmented by energy storage and carbon capture and sequestration {CCS}). But if it fulfills even a portion of its promise, fusion could change society's traditional relationship with energy.

"Fusion is audacious and aspirational, it's always triggered something in people, the idea of leveraging the power of stars," says Dennis Whyte, head of MIT's Department of Nuclear Science and Engineering and director of the Institute's Plasma Science and Fusion Center. "It's a way of saying that we should provide energy to the entirety of humanity in a way that's environmentally responsible and that will last forever."

On paper, fusion is almost ideal: fundamentally safe, no carbon emissions, 24/7 availability, little proliferation risk, powered by fuel that is inexpensive, inexhaustible and equitably distributed. A fusion-based power plant would incorporate one or more reactors where star-like conditions of extremely high temperature and pressure allow atomic nuclei to overcome their inherent repulsion and fuse. This creates a heavier nucleus while releasing energy in the form of heat, which would be channeled to turbines for electricity production.

The concept has been a staple of futuristic literature and movies, and as a result, "there's generally an assumption that it's a good thing," says Michael Delage, chief technology officer of 16-year-old General Fusion. "That's different from the day when you have to build a plant and engage with the local community, but there's a lot of inherent safety." There is no risk of uncontrolled reactions, and while reactor maintenance and decommissioning would result in some radioactive material, "it can be managed on a human time scale—decades and not millennia," notes Delage. Moreover, plants could be located close to where electricity is needed, reducing the need for long transmission lines.

But realizing this vision has proved to be brutally difficult, with dozens of different experimental reactor concepts failing to achieve net-positive energy output.

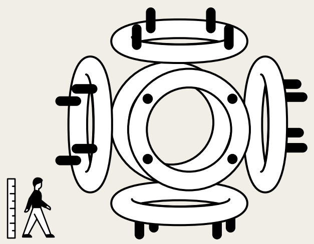
One hurdle has been the need to develop better basic knowledge of plasmas—superheated ionized gases like those found in the core of stars—and an understanding of how to create, maintain, and control them. The field of plasma physics only began to emerge in the mid-20th century, and fusion researchers have made substantial contributions to its advancement.

## An Accelerating Time Frame?

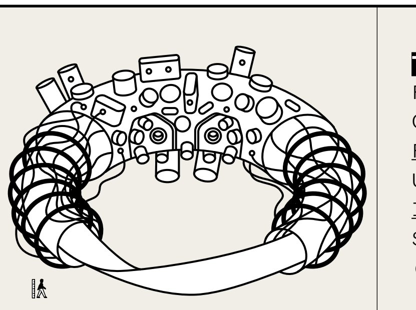
The challenges have been difficult enough that, until recently, even technology optimists did not envision working fusion reactors before the latter half of the century, with 2100 a commonly cited date for commercial availability. The flagship effort to date, the internationally funded ITER project in southern France, is designed to achieve net positive output for limited periods after commencing experiments in 2025, at a cost of over 20 billion Euros, but the nature of its origins and mission mean

## Fusion Timeline

**EMC2 Fusion Development Corp.**
Polywell - Magnetic Cusp Confinement
Founded: 1985;
USA-New Mexico



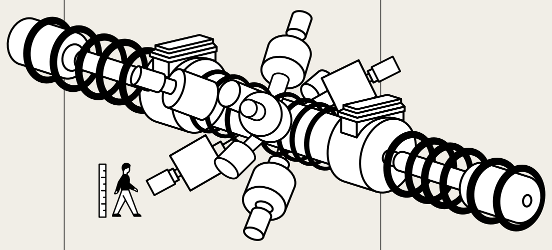
1985



**Wendelstein 7-X**
Stellarator MCF
Founded: 1994;
Germany- Mecklenburg-Vorpommern
Investment:
>€1 billion
Investors: Germany, European Union

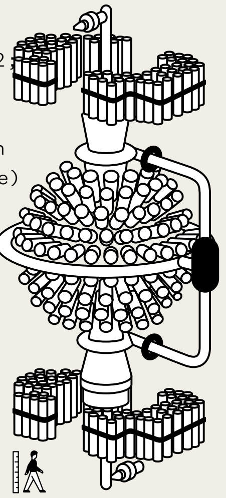
1994

**Tae Technologies**
Field-Reversed Configuration MCF
Founded: 1998;
USA-California
Investment: "Over $500 million"
(per press reports)



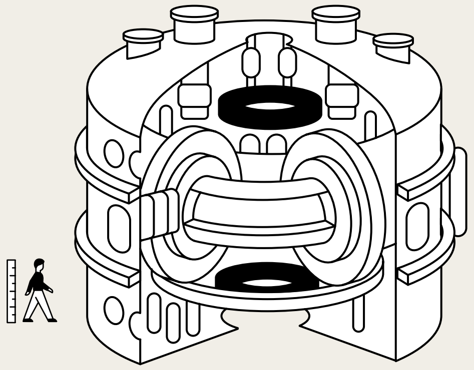
1998

**General Fusion**
Magnetized Target MIF
Founded: 2002;
Canada-BC
Investment:
$89.6 million
(per Crunchbase)

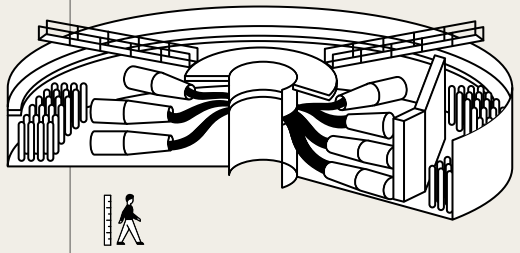


2002

**Korean Superconducting Tokamak Advanced Research (KSTAR)**
Tokamak MCF
South Korea-Daejeon
Fusion research begun 1995;
KSTAR completed 2007



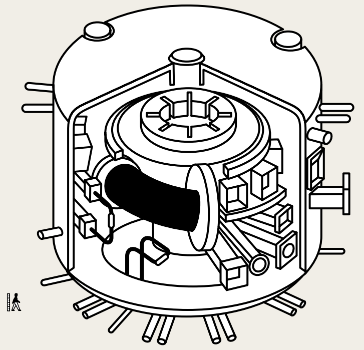
2007



**Sandia National Laboratory -Z Pulsed Power Facility (Z Machine)**
Z-pinch/ICF
USA-New Mexico
Fusion research begun in 1960s, latest upgrade 2007
Investment: $90 million for 2007 upgrade

2007

**ITER**
Tokamak MCF
Founded: 2007; France-Provence
Investment: ~€20 billion
Investors: European Union, USA, China, India, Japan, South Korea, Russia



2007

that it is oriented towards research and not electricity generation.

Other substantial efforts have been underway at publicly funded laboratories in the US, UK, Germany, and China. In addition to advancing plasma science, they have cultivated new sensing and measurement technologies, materials that can withstand the extraordinarily harsh conditions inside reactor chambers, ultra-precise control systems, and a host of other enabling technologies—often in partnership with universities and private contractors.

That evolving fund of knowledge set the stage for the current rise in private-sector activity, and more-optimistic timelines. In 2013, Lockheed Martin announced ambitious plans to demonstrate a 100-megawatt fusion reactor small enough to fit on a truck by 2019, with commercial production five years later. Although they have not provided an official update since then, and were not available for comment for this article, several other companies have put their own stakes in the ground.

UK-based Tokamak Energy has stated a goal of achieving first electricity by 2025 and a commercially viable Fusion Power Module by 2030. TAE's Binderbauer has said the company aims to demonstrate net positive energy by the mid-2020s. And MIT spinout CFS has targeted putting energy on the grid in 15 years.

### "It's Longer Term, But It's Not Crazy"

While those time scales are short by fusion standards, they're long for traditional investors. With so much potential, however, putting money on the table is not out of the question for long-term thinkers, impact investors, and organizations seeking future strategic advantage—especially those willing to manage risk and with an understanding of science and technology, including scaling processes.

Investment is starting to flow from individuals and institutions to the private sector. TAE has received over $500 million over 20 years, from investors such as Microsoft co-founder Paul Allen, Goldman Sachs and Venrock. CFS has an initial $50 million stake from Italian utility Eni, which will also support related work at MIT. The UK's First Light Fusion has raised about $33 million, according to the Crunchbase website, and the list goes on, with Amazon's Jeff Bezos and a range of VC and energy funds investing in General Fusion and PayPal founder Peter Thiel investing in Helion Energy.

Malcolm Handley, a former software engineer who launched the Strong Atomics venture firm to invest in a portfolio of fusion companies, says the case is solidifying. "When I started, I thought it was just impact investing, but as I built the case, people started saying it's not just that—it's a good investment. The first company that demonstrates reactor gain from fusion can almost certainly go public, especially if they have a commercial path. If they can get to that, or a good proxy, in five to ten years, you can invest with relatively normal profit-seeking goals. It's longer term, but it's not crazy." Strong Atomics currently has $4 million invested in four startups (which are also receiving funding from the US Department of Energy's ARPA-E development program) and is planning a substantially larger second phase of investment.

As encouraging as these developments are, says Randall Volberg, executive director of the recently formed non-profit Fusion Consortium outreach organization, funding well beyond current levels will be needed. "NASA has a technology readiness scale that ranges from one, basic observations, all the way to nine, representing commercial deployment. Collectively, we range around two to five, where research continues to prove out the feasibility of the physics while technology is demonstrated using progressively sophisticated prototypes.

"An acceleration is taking place, but there's still a long way to go on the science side. We need nine- and ten-figure level investment, something like $300 million to $600 million for each viable project to be in a position to demonstrate net power at a generator-relevant scale." (To gain more visibility and attract talent and funding to the field, the Consortium is entering fusion as a theme for the 2019 cohort of the XPRIZE Visioneering Program, with an eye towards winning sponsorship for a prize competition starting in 2020.)

Government funding was the progenitor of this new wave of fusion enterprises and will continue to be essential in building additional scientific understanding, just as combined public-private efforts have driven new approaches in space exploration and advanced fission. However, Andrew Holland, Director of Studies and Senior Fellow for Energy and Climate at the American Security Project, notes that Washington is something of a lagging indicator of fusion interest. "At this point for politicians and policy people, fusion is still at the so-what stage," he says, pointing out that 10 to 15 years is a lifetime in politics.

Holland adds, however, that Congress did appropriate a surprising $532.1 million for fusion development in the FY18 budget, including $122 million for ITER and $410 million for the American domestic program, including the DIII-D tokamak research program run by General Atomics and the National Spherical Torus Experiment at Princeton University. That represents a $152 million increase over FY17—but future appropriations are an open question.

What will all that money be spent on? Most will go into design and production of one-of-a-kind machinery and systems for reactors (see sidebar, The State of Fusion). The goal is to create conditions hot enough for long enough, and with enough density of nuclei, for net-positive fusion to occur—a state that meets what's known as the Lawson Criterion, originally defined in the 1950s.

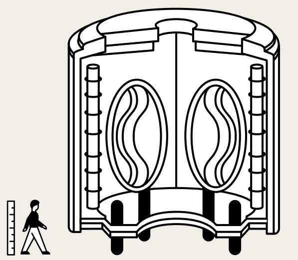
> *Government funding was the progenitor of this new wave of fusion enterprises and will continue to be essential in building additional scientific understanding, just as combined public-private efforts have driven new approaches in space exploration and advanced fission.*

### What Do Potential Customers Want?

Let's assume for the moment that one or more companies or projects manage to meet the Lawson Criterion. At that point, the emphasis will shift to applying the technology in a product that someone will buy.

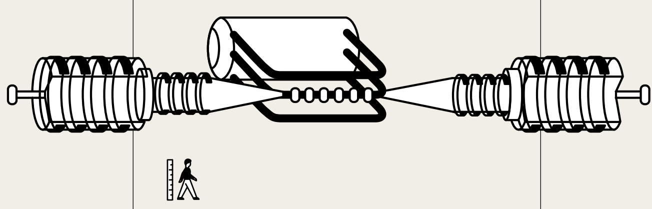
While power grids are evolving, that "someone" is likely to be utility companies, and perhaps the best summary of what they want to buy can be found in a 1994 report from the Electric Power Research Institute (EPRI), the research and development arm of the US utility industry. *Criteria for Practical Fusion Power Systems* identifies three "criterion groups of overarching importance" that are still widely seen as valid today:

**Economics:** "To compensate for the higher economic risks associated with new technologies, fusion plants must



**Tokamak Energy**
Compact Spherical Tokamaks
Founded: 2009;
UK-Oxfordshire
Investment: £22 million
(per company)

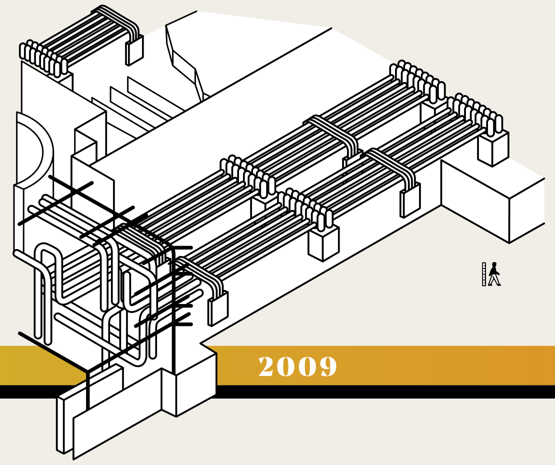
2009



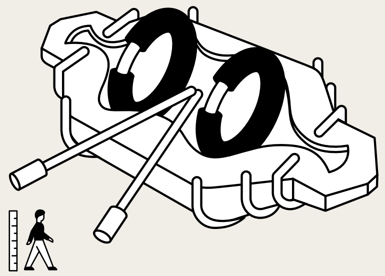
**Helion Energy**
Magnetic Compression MIF
Founded: 2009;
USA-Washington
Investment: $12.1 million
(per Crunchbase)

2009

**Lawrence Livermore National Laboratory - National Ignition Facility**
Laser indirect drive ICF
USA-California
Fusion research begun in late 1950s, NIF completed 2009
Investment: "About $3.5 billion"



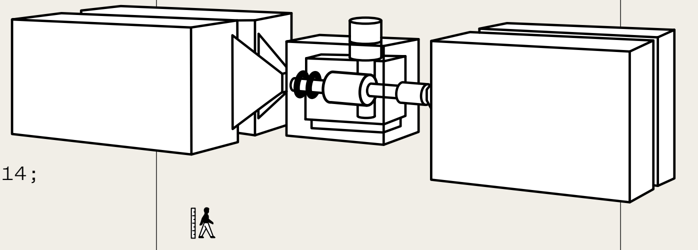
2009



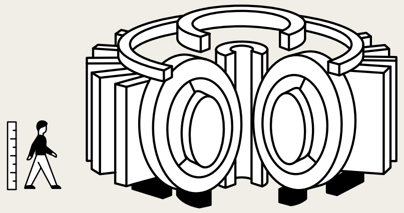
**Lockheed Martin Skunk Works**
High Beta MCF
Program Commenced: 2014;
USA-California

2014

**U.S. Department of Energy ARPA-E ALPHA Program**
Funds multiple early-stage projects (private, academic, national labs) in lower-cost intermediate-density fusion (between MCF and ICF).
Founded: 2014; USA
Investment: ~$30 million



2014



**Commonwealth Fusion Systems**
Compact tokamak MCF
(SPARC, ARC)
Founded: 2018;
USA-Massachusetts
Investment: $50 million
(per company)

2018

have lower life-cycle costs than competing proven technologies available at the time of commercialization.”

**Public Acceptance:** “A positive public perception can be best achieved by maximizing fusion power’s environmental attractiveness, economy of power production, and safety.”

**Regulatory Simplicity:** “Any permitting/licensing process for fusion power plants should be designed to allow issuance of permits/ licenses prior to major capital commitment and for the life of the plant.”

> *The first demonstration of controllable fusion will mark a technological and engineering triumph; if the history of innovation is any guide, there’s a fair chance it could happen in more than one place around the same time.*

This is where the vision of fusion as a world-changing technology must make a practical case: on cost per kilowatt-hour, and questions like how much cooling water a fusion power plant might need, whether maintenance will require radioactive components to be trucked through city streets, what measures are needed to ensure worker safety, and how to make certain a reactor’s rich stream of neutrons can’t be used for nefarious purposes.

These types of issues are likely addressable through a combination of planning, engineering, and regulation, and they will increase with importance along with the chances of actual market uptake.

CFS chief executive Bob Mumgaard speaks in terms of a “social license,” a broad acceptance that has to be earned by any new technology on its merits—from genetic sequencing to electric scooters. He notes that when fission emerged in the 1950s, “it started with a license that it was going to be available to everybody, but then the byproducts of the technology meant it had to be constrained—provided you don’t make bombs with it, you implement it in a way that it can’t melt down, you handle the waste. For fusion we have to work that out, it takes a dialogue, figuring things out with stakeholders. We’re already working on that.”

It’s worth noting that EPRI, which released its last major fusion-oriented report in 2012, plans to take a fresh look at the subject this year. “Based on the growing number of inquiries, greater attention to fusion may be in order,” said Andrew Sowder, technical executive for advanced nuclear technology.

And more broadly, notes Mumgaard, worldwide power grids in 2050 will likely be quite different from today’s, with different models for generation, consumption, and purchase. “That’s an exciting aspect; the fusion industry is navigating changing waters, and we will need to take advantage of and learn from the rise of renewables and other sources.”

## What to Watch For

The first demonstration of controllable fusion will mark a technological and engineering triumph; if the history of innovation is any guide, there’s a fair chance it could happen in more than one place around the same time. What are some intermediate indicators that the milestone might be nearing?

One is new progress towards the Lawson Criterion, especially among technologies that are already relatively close (such as tokamaks and laser-driven inertial confinement fusion). But it’s important to keep in mind, as TAE’s Binderbauer notes, that success on that point does not necessarily translate into commercial viability. There may be a need going forward for separate agreed-upon metrics that can factor in economics.

One intriguing sign is the recent formation of several industry organizations. In addition to the Fusion Consortium, there is now the American Fusion Project (AFP), a spin-out from the American Security Project (ASP), which focuses on educating policymakers, increasing public awareness, and encouraging public-private cooperation.

There is also the Fusion Industry Association, an independent association affiliated with the American Security Action Fund, a 501(c)4 nonprofit. This allows it to lobby and advocate, and provide a unified voice in Washington to call for regulatory certainty, public-private research partnerships, and government financial support to encourage innovation and reduce risk.

Such collaboration between public and private entities could be a boon to potential projects like a materials testing facility, which would stretch the resources of any single company. General Fusion’s Delage notes that there’s already substantial cooperation on simulation and diagnostics, and he cites heat extraction from reactors as something that affects every approach to fusion.

“There will naturally be an ongoing role for government,” Delage adds. “The biotech industry does a tremendously good job of integrating academic and publicly funded research, and commercialization of discovery. We in the physical sciences can learn from them how to get the mix right, and hopefully fusion will find a model—that’s one of the exciting things about CFS and their integration with MIT.”

Another development is the International Conference in Innovative Fusion Approaches which, among other efforts, is seeking to bridge China’s building of fusion capabilities and expertise with the established fusion research community and infrastructure in the West.

One thing that few see happening in the near term is industry consolidation, although it’s not hard to envision a scenario where certain companies might find that access to one another’s IP and expertise could bring results sooner. As MIT’s Whyte says (of CFS, but it holds true for everyone), “there is a 100 percent probability that someone else comes up with a key breakthrough.”

And the fact that there are now more “someone elses” in business than ever before is, perhaps, the most promising sign of all for fusion’s immediate future.+

# The Fusion Landscape

*Concepts and Approaches*

**“Fusion ‘zoology’ can be bewildering to non-experts, and even to some experts,” acknowledges Scott Hsu, a scientist in Los Alamos National Laboratory’s Plasma Physics Group. Let’s simplify the ecosystem.**

## UNDERLYING APPROACH:

### *Steady-State Fusion*

Steady-state approaches strive to generate a continuous flow of heat from a stable plasma at relatively low fuel density and pressure. This requires not only challenging levels of plasma control, but also a reactor vessel that can withstand continuous high-power flux at close range and efficiently divert heat for electricity generation.

### *Pulsed Fusion*

Pulsed approaches dodge some of the inherent difficulties faced by steady-state fusion by compressing or imploding tiny fuel pellets or plasma to extremely high density and pressure for short periods of time (although this also raises new issues to grapple with). The compressed fuel is not held in place; it simply expands back out after undergoing enough fusion reactions to generate net energy gain, with the process being repeated steadily to create a stream of heat for generation purposes. Achieving sufficient stability and energy confinement are fundamental challenges.

## METHOD OF CONTAINMENT:

Multiple approaches can be used to confine the reacting fuel, which is typically some combination of the hydrogen isotopes deuterium and tritium (though use of helium or boron is also being explored).

### *Magnetic Confinement Fusion (MCF)*

No material container can withstand the temperatures needed to sustain fusion; one alternative is a “magnetic bottle” that can contain and manage a steady-state plasma at millions of degrees C.

In the 1960s, Soviet scientists designed an MCF reactor called a tokamak, with a toroidal (doughnut-shaped) chamber, which has since become a primary avenue of development. It is used by the ITER program, and in the MIT research that led to the formation of Commonwealth Fusion Systems, which intends to make the concept less expensive and more compact by applying newly available superconducting magnet materials.

Advances developed in tokamak research are being applied in variations like the stellarator, which is being explored at the German Wendelstein 7-X program, spherical tokamaks (at private companies Tokamak Energy and Applied Fusion Systems), and spheromaks (being developed by CT Fusion). TAE Technologies is focused on the field reversed configuration (FRC), an alternative means of magnetic confinement.

### *Inertial Confinement Fusion (ICF)*

This approach pursues pulsed methods to achieve the Lawson Criterion, heating and compressing a fuel target to very high plasma densities. ICF has been studied in government facilities around the world, including the US, France, and Japan, for materials science and weapons research, as well as energy production, and is being pursued privately by University of Oxford spinout First Light Fusion in the UK.

### *Magneto-Inertial Fusion (MIF)*

MIF combines the compressive heating of ICF with the stability and magnetically enhanced alpha heating of MCF. A number of US national laboratories have pursued it, and Canada’s General Fusion is developing an approach that uses a sphere filled with molten lead-lithium, in which a vortex is formed to contain an injected pulse of magnetically confined fuel (deuterium-tritium). The fuel is compressed to fusion conditions via an array of pistons that squeezes the liquid metal and shrinks the vortex opening. Others developing the concept are startup Helion Energy, 10-year-old Magneto-Inertial Fusion Technologies Inc., and HyperJet Fusion Corp.

## OTHER APPROACHES:

Other companies are pursuing confinement approaches that do not neatly fit these categories, such as Lawrenceville Plasma Physics, which is exploring dense plasma focus technology.

While each approach has its own daunting challenges, there are some general distinctions. “The tokamak and laser-driven ICF are the most scientifically mature approaches, and both are approaching the Lawson criterion,” notes Hsu. “Other approaches are at lower levels of scientific maturity and performance but might reduce the engineering complexity and cost of hypothetical reactor designs. My own view is that, at the present stage of fusion energy development, we should and need to explore many different approaches—the potential benefits are too great to leave any credible stone unturned.”

# The Engine's Portfolio Companies

We invest in the transformative, the audacious, and the new. These companies—and the founders they represent—are working on scientific breakthroughs and converging technologies that hold the potential to redefine the future.

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|---|---|
| Analytical Space | *Space & Internet of Things* |
| C2Sense | *Advanced Materials & Internet of Things* |
| Cambridge Electronics | *Semiconductors* |
| Cellino Biotech | *Biotech & Life Sciences* |
| Commonwealth Fusion Systems | *Energy* |
| Form Energy | *Energy* |
| iSee | *Deep Software & AI* |
| Kytopen | *Biotech, Life Sciences & Advanced Manufacturing* |
| Suono Bio | *Biotech & Life Sciences* |
| Via Separations | *Energy, Advanced Materials & Advanced Manufacturing* |
| Zapata Computing | *Quantum Computing Software* |

# Analytical Space

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| **Founders** | \|**1**\| Justin Oliveira, \|**2**\| Dan Nevius |
| **Background** | NASA, Planetary Resources, White House, HBS |
| **Industry** | Space, Internet of Things |

Satellites gather enormous amounts of data. Data used in climate modeling, city planning, precision agriculture—data used to help feed, organize, and protect our planet. But most of it never reaches the ground. The theoretical pipes are too small and the data flow too irregular. Analytical Space is solving this throughput and availability problem. And it's doing it for earth's existing collection of satellites as well as the rapidly growing sector of small commercial satellites. Their technology is forward-thinking and backwards-compatible.

The solution starts with light. With the same space and energy that traditional radio frequency systems use, light-based communications can send far more data. By operating a network of small satellites, equipped with hybrid RF-optical communication technology, Analytical Space will provide an in-space data relay service, in essence serving as a router for remote sensing satellites. Analytical Space will get more of the important data to those that matter, with greater efficiency at lower cost than previously thought possible.

Unlocking the potential of data from space.


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# C2Sense

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| **Founders** | **\|1\|** Jan Schnorr, Tim Swager, Eric Keller |
| **Background** | Tim Swager Lab MIT |
| **Industry** | Advanced Materials, Internet of Things |

The more we know, the safer and healthier we can become. C2Sense reveals a variety of gases, making them detectable and trackable, helping us put our world, and our actions within it, in perspective. A digital olfactory sensor platform for industry, C2Sense technology transforms smell into real-time data that can be accessed remotely.

With high-fidelity sensors at a low price point, C2Sense will empower a broad array of industries including those involved in food supply, power generation, and chemical production to take control of their environments. Such transparency and control reduces waste, improves the safety and health of employees, and helps us build a more efficient and productive world.

Making the invisible visible.

# Cambridge Electronics

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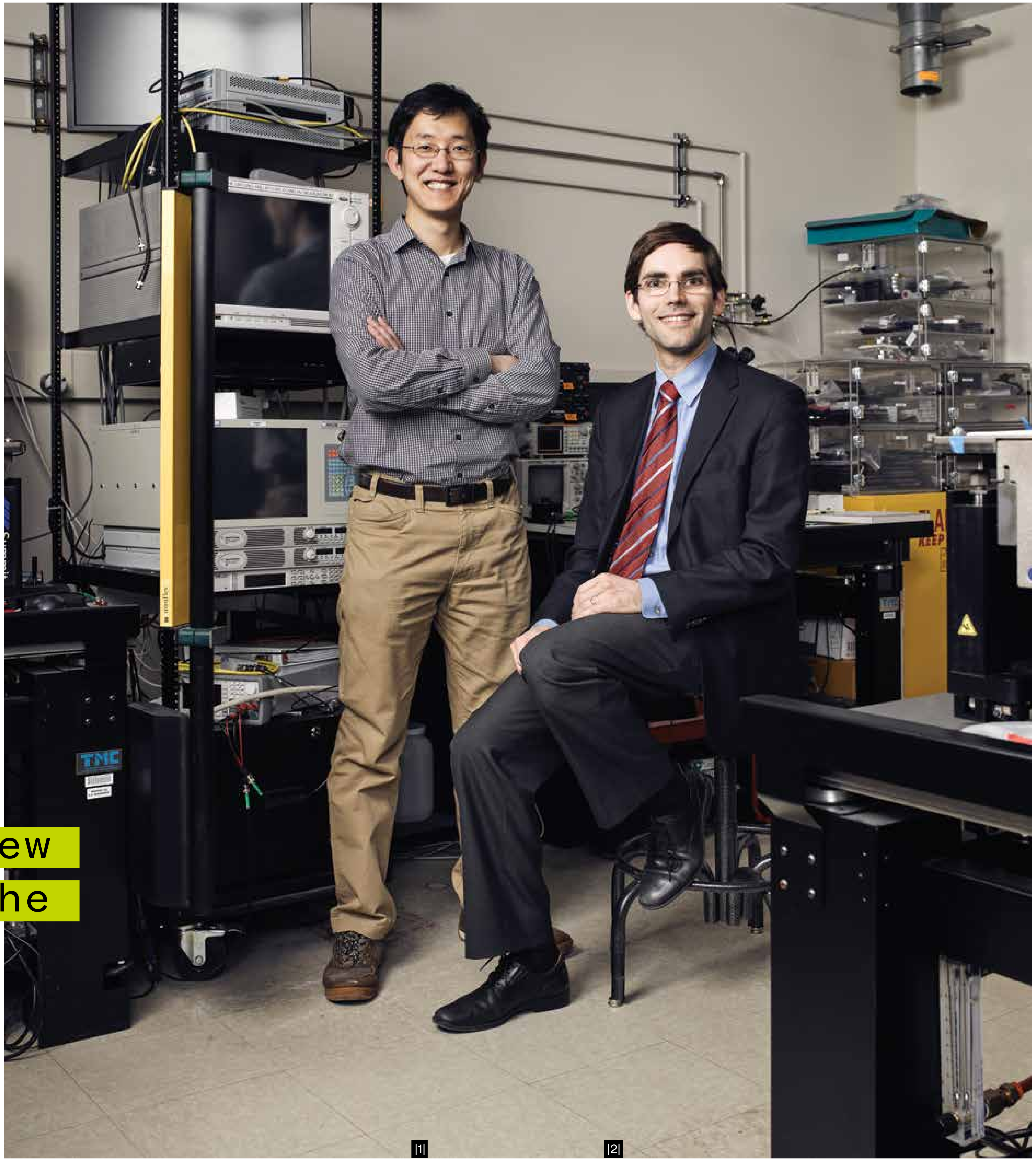
| **Founders** | \|**1**\| Bin Lu, \|**2**\| Tomas Palacios |
| **Background** | Microsystems Technology Laboratories MTL, Department of Electrical Engineering and Computer Science EECS |
| **Industry** | Semiconductors |

Every material has a truth at its molecular level—some are simply born better for certain applications. In the world of energy processing, gallium nitride (GaN) is poised to supplant silicon for this very reason. Its physics works.

Cambridge Electronics is harnessing the inherent benefits of GaN to increase the efficiency of energy processing and management at the chip level by 10 to 20 percent. Those are seismic numbers. The company's proprietary technology is targeted to bring these energy savings to electronics for data centers, electric cars, 5G communication, consumer devices—the entire energy processing landscape. It's efficiency that is poised to transform the future of connectivity, power management, and transportation.

Using a revolutionary new material to transform the world's energy usage.



# Cellino Biotech

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| **Founders** | \|**1**\| Nabiha Saklayen, \|**2**\| Matthias Wagner, \|**3**\| Stan Wang, \|**4**\| Marinna Madrid |
| **Background** | Harvard School of Engineering and Applied Sciences (SEAS), Harvard Medical School, The Church Lab |
| **Industry** | Biotech & Life Sciences |

Stem cell-derived therapies hold the potential to treat many diseases at the cellular level. Made from adult tissue, induced pluripotent stem cells (iPS cells) can generate any other cell type—providing an unlimited supply of therapeutic cells to treat disease. However, the engineering of therapeutic cells from iPS cells is inefficient and expensive at scale. Cellino Biotech is solving this problem with its novel mix of nanotech, optics, and biology.

Cellino has built the first platform that enables precise digital control over cells in their natural environment. Their proprietary delivery technology, NanoLaze, executes the right sequence of code at precise time points, using synthetic biology to precisely control discretize how genes are turned on and off inside a cell. The technology "digitally steers" iPS cells to a target cell type, creating any cell at will."

Cellino Biotech's platform is versatile and robust, and provides the throughput and dependability necessary to transform the biotech industry—it is a platform that will make cell-based therapies a staple of 21st-century medicine.

Enabling cellular therapies using lasers and nanotechnology.

# Commonwealth Fusion Systems

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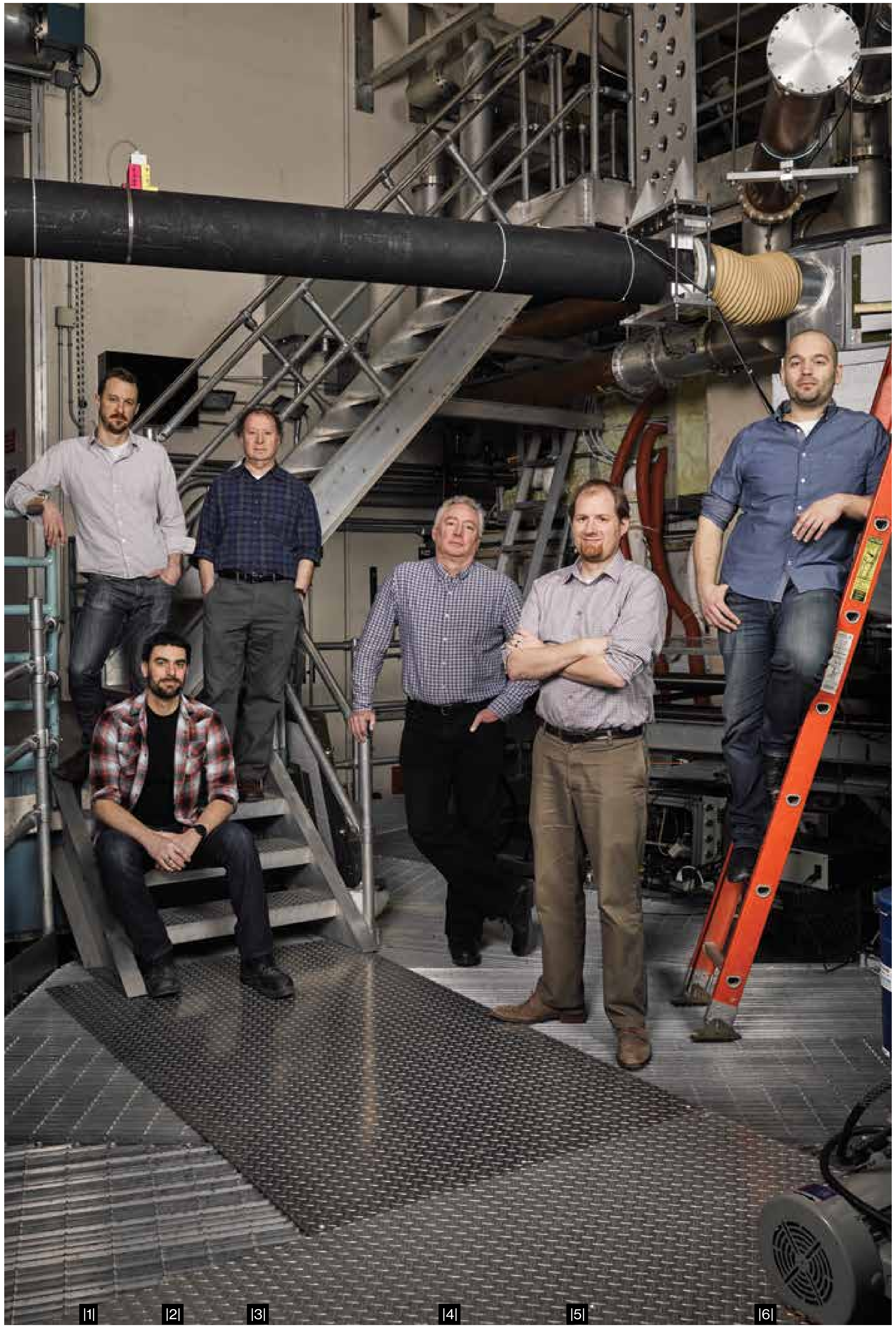
| **Founders** | **\|1\|** Zach Hartwig, **\|2\|** Brandon Sorbom, **\|3\|** Martin Greenwald, **\|4\|** Dennis Whyte, **\|5\|** Bob Mumgaard, **\|6\|** Dan Brunner |
| **Background** | MIT Plasma Science and Fusion Center |
| **Industry** | Energy |

Commonwealth Fusion Systems is at the forefront of the modern fusion movement with its revolutionary magnet technology. Built with yttrium-barium-copper oxide (YBCO), it's tech that can slim down reactor size and cut costs to commercially viable levels, eventually supplanting fossil fuels as the dominant global power source. Such technology will also produce significant increases in power generation to satisfy the demands of an ever more voracious energy-hungry world.

We are on course for a future in which fusion power can claim both financial and environmental victory. Imagine a world with limitless—safe—energy, zero greenhouse gases, and no long-lasting nuclear waste. Because Commonwealth Fusion Systems has.

The fastest path to clean, limitless fusion energy.



# Form Energy

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| **Founders** | **\|1\|** Mateo Jaramillo, **\|2\|** Yet-Ming Chiang, **\|3\|** Ted Wiley, **\|4\|** William Woodford, **\|5\|** Marco Ferrara |
| **Background** | DMSE MIT, 24M Technologies, A123, Tesla Energy |
| **Industry** | Energy |

Form Energy will solve large-scale renewable energy's most fundamental limitation—reliability. And they'll do it with a novel approach to energy storage. Rather than thinking of batteries in the traditional sense, simply as storage vessels, they think of them as bidirectional power plants.

Built to displace fossil fuel baseload generation plants, Form Energy's core technology will store and supply hundreds of megawatts via the existing energy distribution infrastructure. Their technology will power massive facilities—the size of an industrial chemical plant—and with these massive facilities come massive economies of scale. Reliable renewable electricity for less than the cost of coal, gas, or oil.

This future, one in which humanity sources the majority of its baseload energy from renewable power plants, is not one relegated to the realm of the hypothetical. It is tested, achievable and scalable—one that Form Energy will shepherd from the lab into the grid.

Creating a new class of batteries to transform the potential of renewable energy.

# iSee

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| **Founders** | **\|1\|** Debbie Yu, **\|2\|** Yibiao Zhao, **\|3\|** Chris Baker |
| **Background** | MIT Computational & Cognitive Science Group |
| **Industry** | Deep Software & AI |

The AI pioneered by ISEE can understand what we're thinking and the choices we may (or may not) make based on those thoughts. They call it Humanistic AI, and it's built with a unique cognitive core. ISEE is leveraging this AI to create truly safe autonomous vehicles designed to do what a human can—drive 100 years without a fatality. These are vehicles powered by an AI that can proactively react to the unpredictable, not because of coded rules or machine learning, but because they understand.

ISEE's core technology has benefits and applications far beyond mobility. With Humanistic AI on the road, this startup is paving the way for the rise cognitive artificial intelligence in industry and beyond.

Humanistic artificial intelligence.

# Kytopen

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| **Founders** | \|**1**\| Cullen Buie, \|**2**\| Paulo Garcia |
| **Background** | Mechanical Engineering MIT |
| **Industry** | Biotech, Life Science & Advanced Manufacturing |

Cells are stubborn things, their obstinance slows the process of biocatalyst production, a key phase in industrial bioengineering, to a crawl. It means that humans must manually insert genetic material into a cell with a pipette. And even then, the viability of each cell is unpredictable. Failure rates are high. Costs are even higher.

Kytopen can change all that.

With its microfluidic-based tool, Kytopen can accelerate and automate the genetic engineering of cells 10,000x times faster than current methods. And with this speed comes increased cell viability. With greater speed and precision, Kytopen will shift the bioengineering paradigm—it will cut costs in drug development, biofuel manufacturing, chemical production, and more. It will inspire and enable new therapies, all while liberating scientists to spend time on the things that matter.

Infinite possibilities for new, genetically engineered cells.

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# Suono Bio

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| **Founders** | \|1\| Carl Schoellhammer, Robert Langer, Amy Schulman, Gio Traverso |
| **Background** | Langer Lab MIT |
| **Industry** | Biotech & Life Sciences |

Treatments for many of our most insidious diseases are crude and ineffective, whether it be due to anatomical difficulties or the molecules of the treatments themselves. Take inflammatory diseases of the GI tract, for example. Crohn's disease, ulcerative colitis, and IBS—treatments for these take hours or days, are uncomfortable for the patient, and their efficacy is variable at best.

Suono Bio is pioneering a superior treatment modality that is more precise, less intrusive, and more effective than anything currently available. Their secret? Bubbles. Ultrasonic bubbles that accelerate the drug into the tissue, at both a higher speed and higher dosage, directly on target. Bubbles that result in markedly higher efficacy and quality of life.

Suono Bio's initial work with inflammatory diseases of the GI tract will serve as a showcase for the viability of the technology, which has possibilities across the biotech ecosystem. Such ultrasonic therapy is inherently versatile, making it ideal for combating humanity's most pressing health challenges. Depending on the final form factor, Suono Bio's technology can be used to effectively deliver therapeutics for diabetes, cancer, and viral infections.

Ultrasound-mediated drug delivery.

# Via Separations

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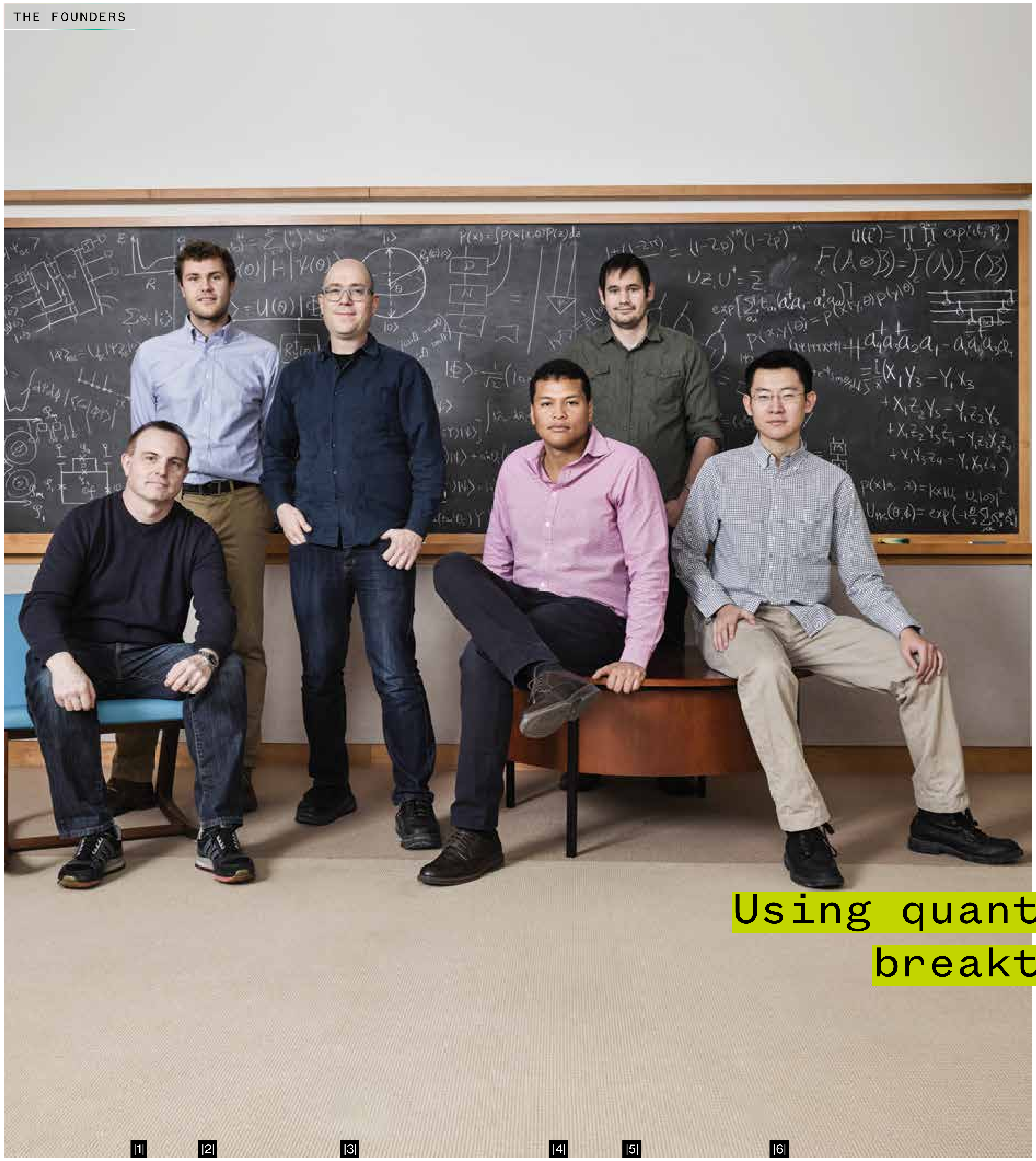
| **Founders** | **\|1\|** Shreya Dave, **\|2\|** Brent Keller, Jeff Grossman |
| **Background** | The Grossman Group MIT |
| **Industry** | Energy, Advanced Materials & Advanced Manufacturing |

Separating things takes energy. A lot of it. 15% of US energy consumption goes into separative processes. But much of this separation remains out of sight—it's an industrial exercise that generates the building blocks for innumerable materials, chemicals, and consumer goods. Think of the massive distillation towers used in the petrochemical industry; running these facilities can account for more than half of an industry's operating costs. Such processes are beyond vital, but they are inefficient. Via Separations exists to solve this efficiency problem.

Wide-scale adoption of Via Separations' technology has the potential to replace thermal separation. It could save the energy equivalent used by the entire gasoline industry every year in the U.S. Their nanoscale membranes are positioned to become the industrial workhorses of an efficient, clean, future.

Massive energy savings from tiny pores.



# Zapata Computing

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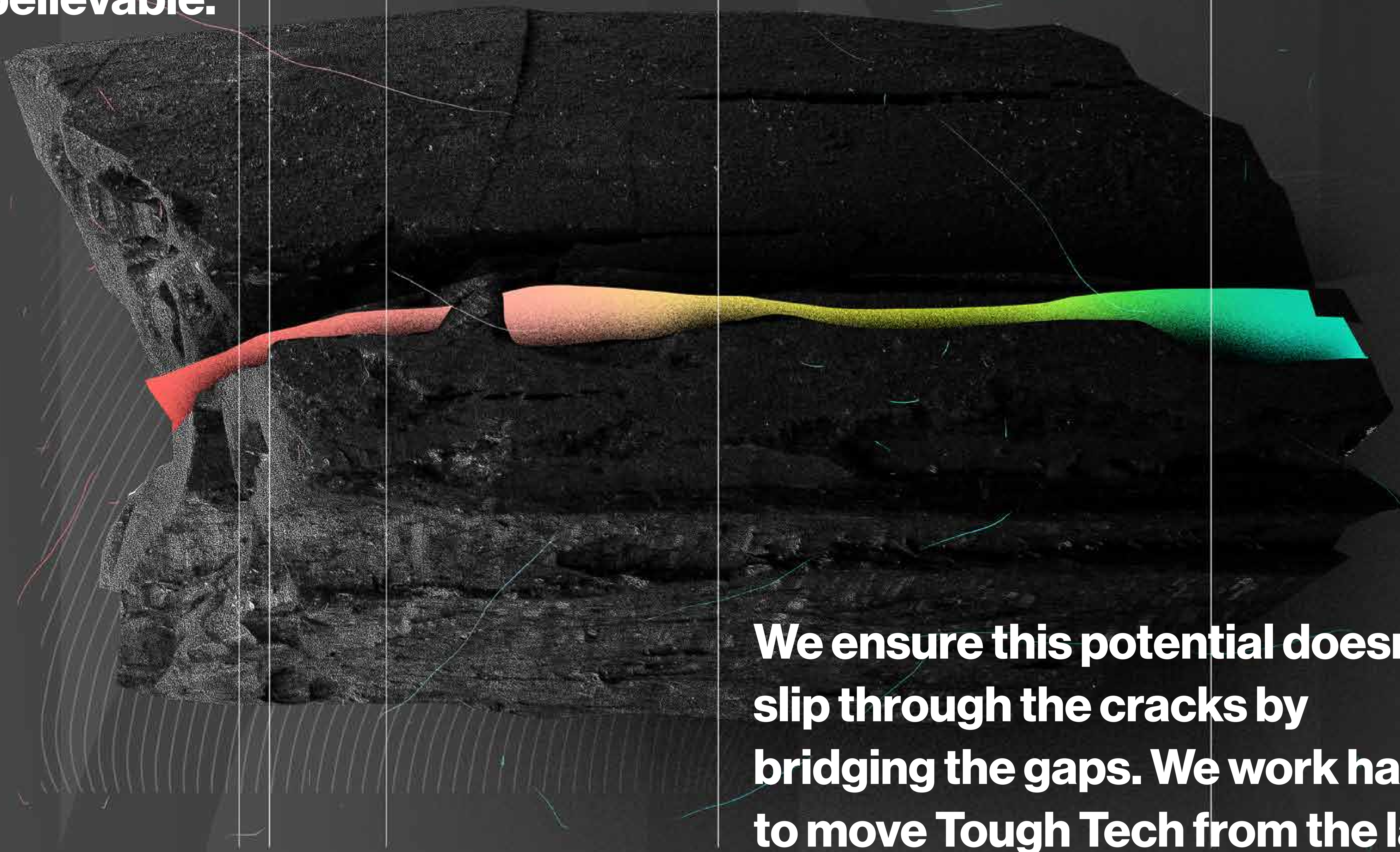
| **Founders** | **\|1\|** Chris Savoie, **\|2\|** Peter Johnson, **\|3\|** Alán Aspuru-Guzik, **\|4\|** Jhonathan Romero Fontalvo, **\|5\|** Jonathan Olson, **\|6\|** Yudong Cao |
| **Background** | Aspuru-Guzik Research Group |
| **Industry** | Quantum Computing Software |

Without an application layer built to harness the raw power and eccentricities of quantum hardware, the technology, no matter how elegant, will remain irrelevant to vast segments of the industrial market. Zapata will change that. Founded by the world's leading expert in applied quantum algorithms, the company is positioned to capitalize on the inevitable reality of the quantum tipping point.

For Zapata, timing is everything. Each day brings us closer to that tipping point—the time when quantum hardware's laboratory success meets commercial viability. The startup's work on quantum computing applications is actually helping accelerate the practicality and speed of quantum computing as a whole. So when that inevitable day does arrive, Zapata will be there, delivering useful quantum applications with the power to transform chemical and pharmaceutical design and optimization on a profound level.

Using quantum technology to create breakthroughs in computation.

We’re here for the long shots, the unimaginable, and the unbelievable.



We ensure this potential doesn’t slip through the cracks by bridging the gaps. We work hard to move Tough Tech from the lab into the light.

Join us for the inaugural Tough Tech Summit and see how some of the world's leading scientists, engineers, and entrepreneurs are helping shape technology that will transform the world.

Equal parts collaborative and visionary, the Tough Tech summit aims to bring together curious individuals interested in learning about, and contributing to, the Tough Tech movement.

*October 29, 2018*
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