ToughTech

A publication by The Engine, built by MIT

FALL 2019

04

INDUSTRY

THE DREAM OF ANYTHING ANYWHERE
NATURE AMPLIFIED
CLEANING UP STEEL

Tough Tech is ...

> Launching a satellite network to connect existing satellites to Earth 24/7.

> A new process to produce steel more efficiently, at a lower cost, and with zero greenhouse gas emissions.

> Developing gas sensing technologies that transform the gases around us into useful, quantifiable knowledge.

> A natural, sustainable, and edible protective food coating that significantly increases shelf life and reduces food waste.

> Transforming power electronics with a new generation of GaN-powered chips.

> Pioneering the next pillar of the regenerative medicine industry through precision cell production.

> Creating safe, unlimited, carbon-free fusion power for the grid in 10-15 years.

> Enabling rapid, accurate diagnosis of infectious disease at the point of care.

> Engineering a bidirectional power plant to make renewable energy available 24/7.

> Producing ultra-efficient chip-scale optical circuits to de-bottleneck data centers, telecommunication networks, and secure quantum communications.

THE ENGINE
Built by MIT

A home for Tough Tech founders.

The Engine, built by MIT, is a venture firm that invests in early-stage companies solving the world's biggest problems through the convergence of breakthrough science, engineering, and leadership. Our mission is to accelerate the path to market for Tough Tech companies through access to a unique combination of investment, infrastructure, and a vibrant ecosystem.

Tough Tech Publication 04

November 2019
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Industry

The way we make things is changing.

Essential things like steel, cement, and chemicals. Everyday things like shoes and tools. Complex things like rockets and biological organisms. This change is thanks to a unique convergence of materials, technologies, and processes maturing in unison.

These new technologies and processes are not simply different from the status quo, they are, in almost all cases, more efficient, less expensive, and far less polluting than their traditional counterparts. This new industrial Tough Tech is developed, in many cases, with the express purpose of tackling the planet's biggest challenges like climate change and human health.

Much of this new industrial revolution is hidden from the public eye — these are technologies and processes that make the things that help us make other things. They are the foundation upon which the necessities of life are built and hold enormous commercial, environmental, and societal value.

This edition of Tough Tech highlights three facets of the Tough Tech industrial revolution: the race to eliminate greenhouse gas emissions from steel, cement, and chemical production; the blossoming and dynamic additive manufacturing industry; and how biology is harnessed to produce industrial products at scale.

THE ENGINE
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Tough Tech Summit℠

Forging a Path for Tough Tech.

Our second invite-only conference of founders, investors, academics, policy makers, and business leaders explored the challenges of bringing Tough Tech to market, and investigated the business, technical, and financial strategies needed to accelerate the commercial success of world-changing companies.

Build 10.21. | Invest 10.22.

Day one, Build, featured a fireside chat with Vinod Khosla, founder keynotes, case study workshops, and interactive panels. Attendees worked together to help solve some of the core challenges faced by Tough Tech companies.

During day two, Invest, founders pitched their businesses and connected with other Tough Tech founders and investors. Josh DeFonzo, Peter Hebert, and Bijan Salehizadeh, some of the lead investors, advisors, and executives behind Auris Health, had a frank and illuminating discussion about the company's journey from startup to multi-billion-dollar acquisition. The day also featured panel sessions and open networking time.

"Solving the global-scale problems Tough Tech companies are tackling requires commitment and collaboration. The only way we solve fundamental challenges in climate, human health, infrastructure, and computing is together."

The Tough Tech Summit has one goal — unite a community to support founders as they build companies tackling some of the world's hardest problems. I saw 500 individual members of such a community — entrepreneurs, academics, policy makers, business leaders, investors, and the founders themselves — work together over two days to push these companies, and their ideas, forward.

All were there because they believe in the convergent power of people, technology, and science to change the world. It was as humbling as it was inspiring.

As you browse this publication, I hope it inspires you to ask yourself how you can help founders' ambition scale to the level where their companies thrive commercially. I challenge you to ask yourself how you can make the path faster and easier for these entrepreneurs — if we all do that, imagine what we can create! If we get it right — *when we get it right* — we can create a Tough Tech ecosystem that needs no introduction.

Katie Rae
CEO & Managing Partner

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500 UNIQUE ATTENDEES

DAY 1: **192** UNIQUE ATTENDEES

DAY 2: **101** UNIQUE ATTENDEES

DAY 1 & 2: **207** UNIQUE ATTENDEES

Build 10.21. — DAY 1

33% ENTREPRENEURS

27% INVESTORS

TOUGH TECH FOUNDERS AND ENTREPRENEURS
123

MEMBERS OF THE TOUGH TECH ECOSYSTEM
39

ATTENDEES
399

MEMBERS OF GOVERNMENT
16

STRATEGIC CORPORATES
45

LEADERS IN ACADEMIA
36

INVESTORS
107

Invest 10.22. — DAY 2

28% ENTREPRENEURS

40% INVESTORS

MEMBERS OF GOVERNMENT
17

MEMBERS OF THE TOUGH TECH ECOSYSTEM
18

TOUGH TECH FOUNDERS AND ENTREPRENEURS
81

ATTENDEES
306

STRATEGIC CORPORATES
32

INVESTORS
122

Platinum Partners

U.S. ARMY · DEVCOM Army Research Laboratory · Breakthrough Energy Ventures · HYUNDAI CRADLE · PNC BANK

Gold Partners

Arrow Five Years Out · BREX · Bayer | Life Hub Boston · Camber Road Partners · First Republic Bank · Foley Hoag · Gunderson Dettmer · MARS · Mintz · SVB Silicon Valley Bank

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Tough Tech Summit℠

Build 10.21.

“To us at The Engine, the future will be filled with more empowered founders building technology, teams, and companies. And those companies will know where to look for support.”

“We have one goal today: to further develop a community that supports these founders as they build companies tackling some of the world’s hardest problems.”

Katie Rae

CEO & Managing Partner, The Engine

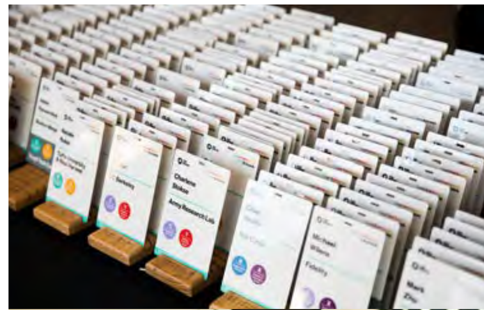
“The team you build is the company you build.”

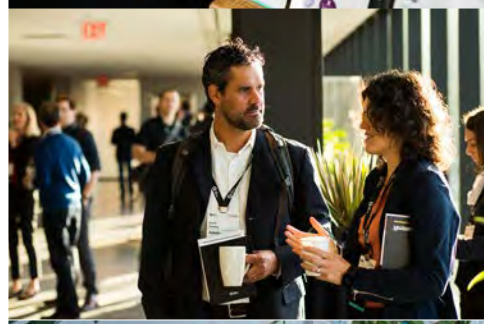
“Skeptics have never done the impossible. Keep that in mind. It’s religion for me. I’d rather try and fail than fail to try it.”

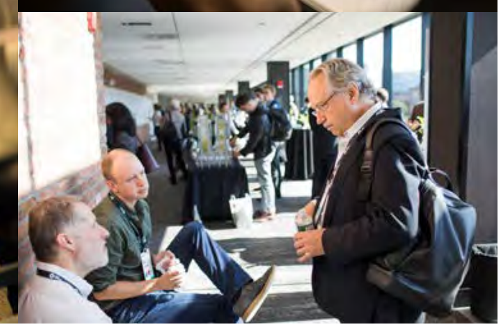
“If you ask three experts and all three say, yeah, this is not doable, then you have to worry. If they all say it’s doable, then you have to worry that too many people will do it. So you have to exist in this other space where people doubt it can be done.”

Vinod Khosla

Founder & Partner, Khosla Ventures







Case Studies

A Business Model Strategy

SOLIDIA TECHNOLOGIES

Ann DeWitt | Moderator
General Partner, The Engine
Jim Matheson | Moderator
Senior Lecturer in Business Administration, Harvard Business School
Nick DeCristofaro
CTO, Solidia Technologies

As Solidia Technologies, a sustainable cement and concrete technology company, began its path toward commercialization, it was faced with a core business model decision — become a cement and concrete company and seek to disrupt the industry's major players, or become a technology provider and disrupt the industry's carbon footprint without being disruptive to established business and manufacturing processes.

Solidia decided to think big — to sell its technology to major manufacturers of cement and concrete, taking advantage of the established global supply chain to scale quickly and efficiently. With this business model, the company's technology has the potential to eliminate at least 1.5 gigatons of CO_2 per year.

Nick DeCristofaro, CTO of Solidia, shared four reasons why his company decided to pursue its current technology-provider business model:

- The logistics of starting our own cement and concrete company are complex — we know cement really well, but do not know the other minerals and materials as well
- We did not want to alienate the existing cement and concrete industry
- We wanted to avoid the massive up-front CapEx
- There are fewer upsides when considering profit and sustainability

What we learned:

"When you're creating a business model, don't be afraid to think big. But with ambition and vision comes the need to educate yourself, and everyone involved, on the policy and regulatory nuance that can impact your plan."

"Before you execute a major strategic decision, always assess the potential tradeoffs between impact and speed. Will moving quickly reduce the impact of that decision?"

B Supply Chain Strategy

FORMLABS

Milo Werner | Moderator
Partner, Ajax Strategies
Max Lobovsky
Co-Founder & CEO, Formlabs
Dávid Lakatos
Chief Product Officer, Formlabs

In 2011, Formlabs was in its early days, working on a prototype for a low-cost, prosumer-oriented stereolithography 3D printer. With the long-term vision of internalizing key parts of their supply chain, they were looking for an immediate partnership that would help them hit the ground running.

In just a few years, Formlabs has grown to be the largest part of their partner's business, with the expectation of overwhelming their production in the near future. With the desire to have more control over its supply chain at current and future scale, Formlabs is faced with a number of options: acquire their current partner, find a new, bigger partner, or build their own facility.

What we learned:

"Maintaining control of supply is super important for us. In the 3D printing world, your material is your special sauce. People are buying your printers for their performance. Formulation is as important for Formlabs as it is for Coca Cola — we wanted to have control of the supply."

"In executing an acquisition, the people on the other side are a super-important part of the negotiation. Some at the company may be in a position to sell and retire, others may want to grow and do new things. Understanding these audiences and their motivations are critical."

"Being the biggest customer of an acquisition target can be very helpful in the negotiation."

C Partnerships Strategy

D-WAVE & LOCKHEED MARTIN

Reed Sturtevant | Moderator
General Partner, The Engine
Vern Brownell
CEO, D-Wave
Ned Allen
Chief Scientist, Lockheed Martin

When D-Wave built the first working quantum computer, it had no customers. How did it sell this computer, a technology that no one had ever bought before? And why did Lockheed Martin, D-Wave's first customer, take the leap and make the purchase when there was no precedent for doing so?

For Lockheed Martin, who produces complex cyber-physical systems, the possibility of reducing the cost and time of software verification and validation (V&V) was too great to ignore. Lockheed spends tens of millions every year on V&V — in fact, 60 percent of production cost is related to V&V of the system. It is, in the words of Ned Allen, the company's chief scientist, "a humongous problem."

Allen at Lockheed had to ensure that the money his company invested in D-Wave's quantum computer would not be lost, even if the initial goal of the program was not realized. Through the case study session, he and Vern Brownell, CEO of D-Wave, described how they used financial offsets by the Canadian government (D-Wave is based in Vancouver) to reduce the financial risk of the investment to near zero.

What we learned:

"Uncertainty is much more profound than technical risk. Technical risk assumes you know what you are doing. This was real research into the unknown."

"Lockheed bought a D-Wave quantum computer for $10M, but the Canadian government offset this investment by $110M. Lockheed and D-Wave had reduced the uncertainty of investment — they had reduced the financial risk (not technical) to almost zero."

"There are literally trillions of dollars per year in offset financing. You can no longer ignore it. And, critically, it allows you to take much higher technical risk than a logical VC would take. That's how tech will move forward."

Panel Sessions

X — Building & Leveraging Board

Katie Rae | **Moderator**
CEO & Managing Partner, The Engine
Andy Wheeler
General Partner, GV
James Geraghty
Chairman, Orchard Therapeutics
John Santini
President & CEO, Vergent Bioscience
Jill Smith
Experienced Global Tech CEO, Non Executive Director & Chair
Jak Knowles
Vice President of Venture Investments, Leaps by Bayer

What we learned:

First-time Tough Tech founders must understand the nuances of building and managing a board of directors before they receive significant investment. A successful board of directors will help a founder bring in new capital, hire staff and advisors, and work through complex deals / contracts. All members of the board should share a deep sense of mission and treat each meeting as an opportunity to collaborate and grow the company.

"As a CEO, you should have one degree of freedom from any member of your board of directors."

"A BOD meeting should not be a company update — use it for the tough questions. Be sure to prep company updates ahead of time and expect that the BOD reads them."

"CEOs should expect a BOD member to bring new capital, help hire staff and advisors, work through specific types of deals and contracts, advise on people management, and use their diversity of experience to fill experience gaps."

"The management of top companies usually reserves time with BOD members outside of BOD meetings to build relationships."

"Leadership should inform the BOD when they are facing massive technical risk, without including them in the technical program."

"If you want to become a more effective BOD member, you must develop a sense of self-awareness — know what you know and you don't know."

Y — Building Technical Teams

Ilan Gur | **Moderator**
CEO, Activate
Tyler Ellis
Founder & Principal, Black Hills Partners
Shannon Miller
CEO & Founder, EtaGen
Matt Verminski
Former VP of Engineering, Desktop Metal
William Woodford
CTO & Co-Founder, Form Energy

What we learned:

The most successful Tough Tech teams strike a balance between those guided by experience and those compelled to explore. While experience can help guide the team through periods of uncertainty, it is inherently biased, often sidestepping new, creative ideas in favor of the status quo. On the other hand, there should be team members who productively question convention. It's important to note that these roles should not be defined by age. Instead, they should be thought of as elements of an employee's character.

"When you are building a technical team, it is essential to have clear targets. Measures of success should be in relation to where you need to get to, not where you started from."

10 hiring tips sourced from the audience:

- *Whiteboard with a person before you hire them. See how they think.*
- *Keep a big list about the kinds of people you want to hire — not just for the immediate opening, but for the next few rounds.*
- *Embrace contracting. It can be difficult to make that first step, so make a contract project.*
- *Be opportunistic — find people between jobs, end of careers, beginning of careers.*
- *Do great phone screens.*
- *Hiring is a mutual decision, try to understand where they are coming from.*
- *Create a scorecard and keep an archive of those scores in Excel.*
- *Know who an interviewee wants to be.*
- *Put people in the shoes of the actual worker.*
- *Get your investors, your network, everybody to start searching for potential candidates.*

Z — Building Your Organization

Albert Lee | **Moderator**
Design Partner, New Enterprise Associates
Katie Burke
Chief People Officer, HubSpot
Patrick Sobalvarro
Co-Founder & CEO, Veo Robotics
Sandra Glucksmann
President & CEO, Cedilla Therapeutics
Lou Cooperhouse
President & CEO, BlueNalu
Ramya Swaminathan
CEO, Malta

What we learned:

Building a Tough Tech organization is about balance. Balancing those with deep domain experience and those who have innate ability. Balancing, as one participant noted, "authors and editors" — authors are those who love to create, editors are those who love to modify. During periods of growth, a Tough Tech CEO must shift roles between teaching, mentoring, and coaching, harnessing the most effective facets of each role to help the team — and the organization — reach its goals.

"As a leader, you really have to be conscious of what constitutes personal growth for different people. People have different goals. It's incumbent on the company, particularly in a competitive environment, to understand this. It's not a one-size-fits-all."

"If you don't invest early in a diversity and inclusion policy, you'll always be playing catch-up."

"There's teaching. There's mentoring. And there's coaching. Good leaders shift between these modes to help their employees get to the right answers."

"Rather than assuming what people want, we remove barriers for people to be able to do more interesting work. Rather than assuming what they want in compensation and equity, we ask them what they want and tailor our benefits packages accordingly."

"It's about remembering that, in a leadership position, your job is no longer to read the scientific paper. It's a constant balance of who do you include and how do you motivate."

Founder Keynotes

"Competing against no one is much better than competing against someone."

"Disruption can create markets."

"I think tech people don't worry about user interfaces...we all get frustrated with bad user interfaces and they abound in tech."

Rodney Brooks

Founder & CTO, Robust.AI

"Nothing motivates your team like having a personal connection to the people who are gonna use their tech. I've come to believe this is fundamental human nature."

"Bring your users into the design process early — from day one."

Keenan Wyrobek

Founder, Head of Product & Engineering, Zipline

"Why did I choose to work at Commonwealth Fusion Systems? It was important for me to fix up this current planet before focusing on getting off of it."

"What do the laws of physics and not historical precedent tell you are possible?"

Joy Dunn

Head of Manufacturing, CFS

"We embrace what we hear from our customers, instead of trying to invent around it. It's been one of the most important things we do as a company."

"Anytime it appears there might be a disconnect between a belief system and what the circumstances are today, you should trace why you got to where you are in the first place."

Geoffrey von Maltzahn

Co-Founder & CIO, Indigo Ag

"You have to both be immodest and very modest at the same time. If you can't raise money, it's not because you're not handsome enough or beautiful enough ... it's because the story isn't a good story or the value proposition isn't a good value proposition."

"If you have a great problem, you can attract great people — you can attract great investors."

Stan Lapidus

Managing Director, Lapidx Research

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Tough Tech Summit℠

Invest 10.22.

"Our experience over the last few years makes it clear — the next wave of Tough Tech is here. And it is working."

"Urgent problems can be solved across all parts of the economy when two things happen: the right policies and the right financial support. Whether it is a radically new way to grow food, new cures for disease, providing clean baseload energy, or computing on qubits to leapfrog Moore's law. With success, these technologies will serve the betterment of humanity. We will launch entire new industries and will create enormous wealth."

"Tough Tech is everywhere. It's the underpinnings of the global economy — today — and in the future. It is the stuff of enduring value. Tough Tech serves as the platform upon which our world is built."

"We need to capitalize on Tough Tech opportunities. To think outside the box and build a different investment paradigm — one that focuses on the full capital stack."

Katie Rae

CEO & Managing Partner, The Engine

AURIS™

Case Study | Auris Health

Josh DeFonzo, Peter Hebert, and Bijan Salehizadeh joined The Engine General Partners, Reed Sturtevant and Ann DeWitt, on stage and provided unvarnished perspectives on shepherding Auris Health from its earliest stages through its multi-billion dollar acquisition by Johnson & Johnson in late 2019.

The trio spoke openly about the challenges of building the company, including the significant strategic decision to avoid traditional medical device investors. "At no point in time did we go to any medical device investor between the Series A and the Series D," Hebert told the audience. To the team, Auris was not a medical device company, but rather a technology company, and one that would benefit from sophisticated, and perhaps unexpected, investors like large global hedge funds and mutual funds.

Hebert elaborated on the advantages of this strategic shift: "These investors were willing to take a leap of faith that Auris is actually fundamentally a technology company that would be valued more like a technology company. And so the terms and the valuation that we ultimately got was much larger than what any of the other traditional medical technology firms could provide. These were on the order of hundreds of millions of dollars versus the millions or tens of millions ...we felt that it would actually translate into this narrative ... people, and ultimately Johnson & Johnson ... believed that this was an only-in-class trophy asset in a technology stack. If they did not get Auris, there was just nothing else behind it."

DeFonzo, Hebert, and Salehizadeh also spoke at length about product development strategy. The team realized that it was essential to recruit Fred Moll, the legendary entrepreneur and technologist behind a monopolistic adjacent company (Intuitive Surgical), to co-found Auris. "We were going to do the Steve Jobs "NeXT" story. We were going to get the guy who started the thing, which is now the monopolistic player, and we're going to fund him to come and kind of beat his original product with a new thing. And it was really as simple as that. That was all I wanted to fund," Salehizadeh recounts.

For the team of entrepreneurs and investors behind Auris Health, the company's eventual multi-billion dollar acquisition was never guaranteed. The decade-long journey from idea to acquisition required 10 times more investment capital than initially estimated and multiple significant pivots. As Auris' DeFonzo tells it, "There were just dark days ... it was about perseverance. We just had to absolutely grind through those things." For the entrepreneurs in the audience, especially the first-time Tough Tech founders, this is one observation that should prove especially sage.

"In capital-intensive businesses, getting your approach right is everything. Sometimes it feels like your fast-twitch fibers aren't being satisfied if you're not doing something immediately with the product or the tech. But I've learned to be patient. To really listen and be aware. To make sure that you're getting requirements right, because in Tough Tech, pivots are costly."

Josh DeFonzo

COO, Auris Health

"With the benefit of hindsight, so many successes just look like a clear linear path, but I'm here to tell you on the ground it will get ugly, it will get messy, and it will get scary. And you need a lot of luck."

Peter Hebert

Co-Founder & Managing Partner, Lux Capital

"If you're an entrepreneur, you should think strategically about who you bring into your next round, not just the valuation, not just a single person. Not just those things, but actually the investors — the firms and the network of relationships they have with future capital providers — I think those considerations are absolutely vital and sometimes overlooked."

Bijan Salehizadeh

Managing Director, NaviMed Capital

Panel Sessions




A
Financing by Strategics

FINANCING BY STRATEGIC CORPORATES

David Gammell | Moderator
Partner, Gunderson Dettmer
Christine Brennan
Partner, MRL Ventures
Dipal Doshi
President & CEO, Entrada Therapeutics
Mateo Jaramillo
CEO & Co-Founder, Form Energy
Max Pieri
Clean-Tech Director, Eni Next

What we learned:

Tough Tech founders interested in pursuing strategic corporate investment should start early. With diverse incentives and more bureaucracy, it's a much longer game than VC. That said, a corporate's expertise and experience can prove invaluable to a Tough Tech startup facing technical challenges.

Corporate investors can provide large amounts of follow-on capital, when appropriate. They also are generally more insulated from economic downturns than a typical VC, with the ability to continue to provide capital when others cannot.

"It is always useful to get a corporate's view on how to approach key technical challenges and milestones. Their expertise and experience can help an early-stage Tough Tech innovate more efficiently."

"As a startup negotiating deal terms, it's important to avoid being backed into a corner by a corporate VC."

"A benefit of having a corporate investor is the large amounts of follow-on capital they have available to tap into."

"The world of corporate venture capital is diverse — it is crucial to understand the individual investors and their processes."

"Pursuing strategic corporates is a longer game than VC, so start early and have more than one option."

"Corporate venture capital may be considered a steadier source of capital, especially during periods of potential downturns."

B
Navigating Capital Markets

NAVIGATING CAPITAL MARKETS: FROM SEED TO INSTITUTIONAL INVESTORS

Andrew Boyd | Moderator
Head of Global Equity Capital Markets, Fidelity Investments
Karey Barker
Founding Managing Director, Cross Creek
Jonathan Hausman
Managing Director and Head of Global Strategic Relationships, Ontario Teachers' Pension Plan
Brian Korb
Managing Director, Solebury Trout
Chris Pike
Managing Partner, Advent International Corporation
Libby Wayman
Investor, Breakthrough Energy Ventures

What we learned:

Tough Tech founders should realize that it is never too early to engage with institutional investors. These investors must understand the technologies and companies that have the potential to disrupt their existing portfolio.

Institutional investors may be led to Tough Tech companies through the peripheral technologies required to complete significant infrastructure projects. If an investor is funding development of a highway, for example, they may be introduced to those innovating in materials, AI, and imaging. Tough Tech founders should be aware of these tangential opportunities.

"If I am valuing something completely new, something that has never been done before, I assess potential impact, the novelty of the technical approach, the team, the markets, and general investment details."

"Remember, investors invest towards milestones."

C
New Models for Government

NEW GOVERNMENT MODELS FOR FOSTERING TOUGH TECH COMMERCIALIZATION

Orin Hoffman | Moderator
Venture Partner, The Engine
Travis McCready
President & CEO, Massachusetts Life Sciences Center
David Stapleton
Acting Deputy Assistant Secretary of Defense for Industrial Policy, U.S. Department of Defense
James Zahler
Associate Director for Technology-to-Market, ARPA-E
Tex Schenkkan
Director, National Security Innovation Capital DIU
Eric Toone
Executive Managing Director and Science Lead, Breakthrough Energy Ventures
Brad Ringeisen
Office Director of the Biological Technologies Office, DARPA

What we learned:

While grants are the most well known and popular sources of government funding for Tough Tech startups, they are not the only option. The Defense Innovation Unit, for example, provides pilot contracts for commercial innovation for technologies that solve DOD problems.

A Tough Tech startup's technology is not required to be solely beneficial to the DOD to receive grants from the organization. Founders should consider grants one step on the path to commercialization — not a means in and of themselves. Many government program managers avoid "grant shops," or entrepreneurs with a history of funding their companies solely through grants.

"Commercially minded Tough Tech startups should not overly rely on government grants. Grants are excellent means to an end, but should not be a means in and of themselves."

"Don't be afraid of the Department of Defense. Any technology can be spun into an application for DOD."

"Build a personal relationship with your program manager. Know what they're looking for before you apply — these relationships will save enormous amounts of time and energy on the application processes."







Y Z Pitches

Pitch Sessions

2 hours. 16 Tough Tech pitches.

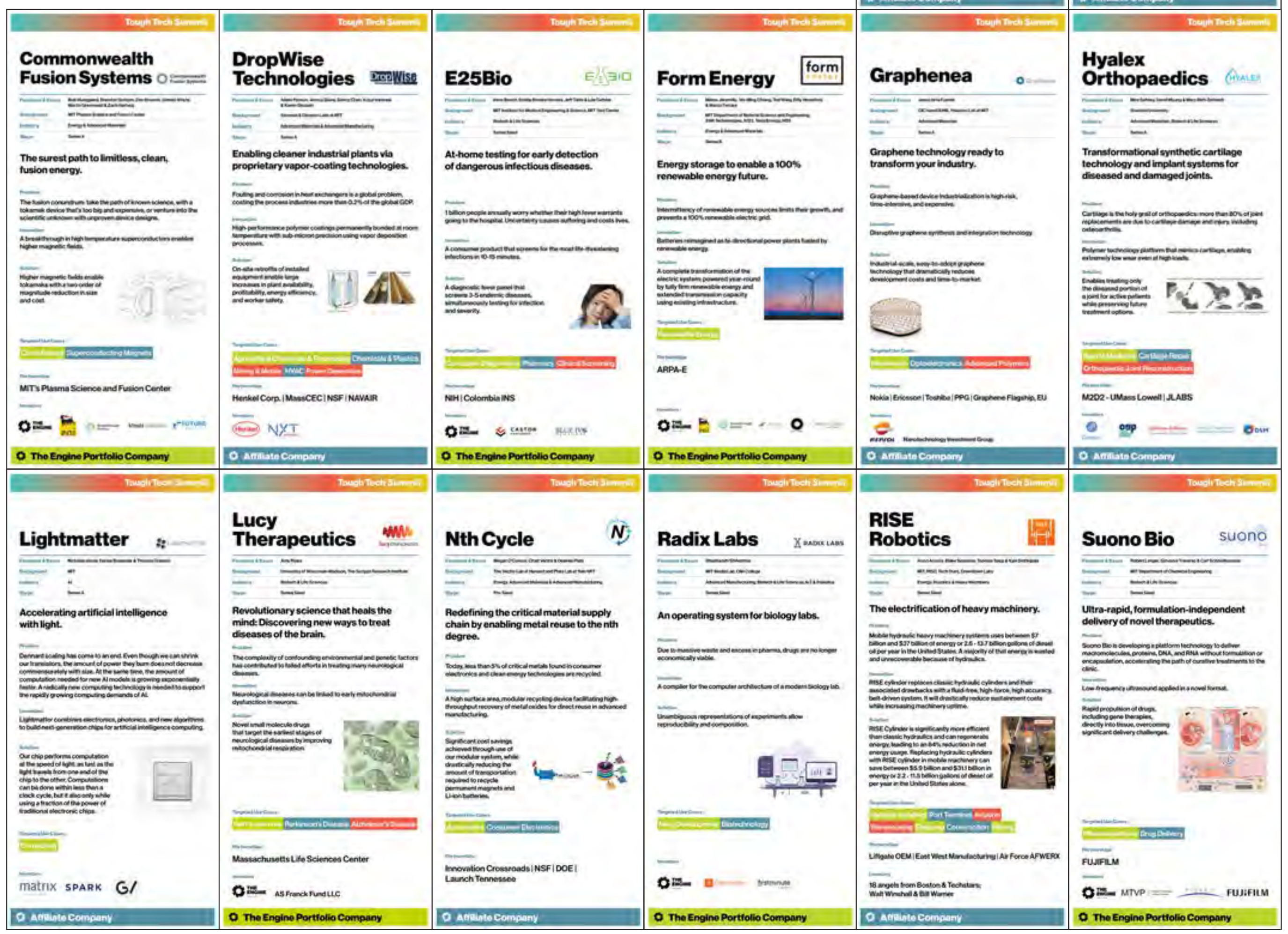






Tough Tech Summit℠ 2019

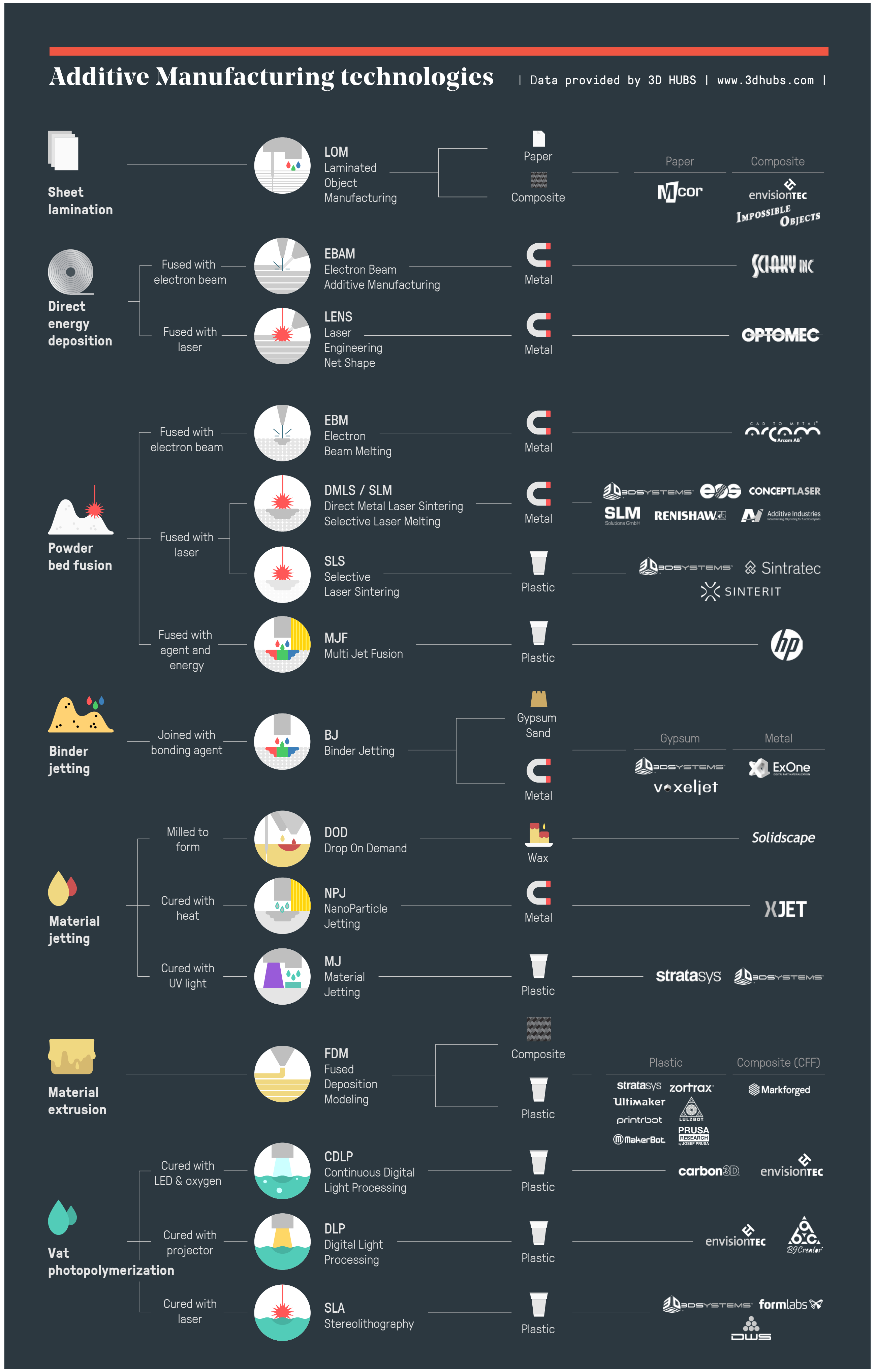
Tough Tech Companies



The dream of ANYTHING ANYWHERE

For decades, 3D printing has seemed to hold a magical potential to build objects out of almost thin air. Is it finally starting to live up to the hype?

By *Michael Blanding* for *The Engine*
Illustrations by *Rodrigo Larraín & Julie Carles*



It's a busy Friday afternoon at Desktop Metal's warehouse-sized office and factory space in Burlington, Mass. Men and women in business suits and khakis bustle around the entryway, picking at catering plates with sandwiches and cookies, while dozens of coders sit crammed into workstations in every inch of floorspace. “I'm super double-booked here, I've got customers, VARs, resellers …” says CEO Ric Fulop, apologetically, as he plops into a chair in a conference room.

He can be forgiven for seeming so stressed. In the three years since its founding, Desktop Metal has raised nearly $450 million in venture capital for its metal 3D printing technology. In January, it reached a valuation of $1.5 billion, achieving “unicorn” status, and giving hope to an industry that has at times seemed more hype than reality. “There is no hype,” Fulop insists. “Thirty years ago, it was a zero billion dollar industry. When we got into this three and a half years ago, it was a $5 billion industry. Now it's a $9 billion industry. We think it's going to be 10 times bigger over the next decade.”

At the heart of Desktop Metal's breakthrough technology is a new printing process that builds up metal objects layer by layer, and then fires them in an oven to harden them. “By separating the shaping of the part from the thermodynamics, that allows us to make printers that are cost-effective and fast enough for mass production,” Fulop says. Its Studio System, suitable for small businesses and machine shops, goes for around $750,000, while its Production System machines go for upward of $1.5 million, designed for high-throughput industrial manufacturing.

“I have a small part I could show to you in the back,” Fulop says. “One machine does a quarter-of-a-million parts per day — it's a hundred times faster than the previous generation technology.” In addition, the process uses much less metal powder than previous techniques, so instead of costing $1,000 per kilogram of parts, it costs $50. “So it's a 20th the cost for a finished part.” With efficiencies like that, he says, 3D printing could compete with mainstream manufacturing processes. “That's where we are going with our Production System — we can enter the market where a lot of the capital gets spent.”

An Industry on the Cusp

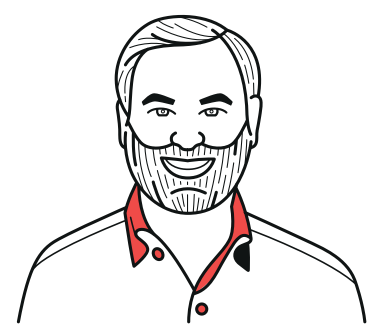
Neal Stephenson's 1995 science-fiction book, *The Diamond Age,* imagined a world in which families of the future could create anything they wanted on a specialized machine called a matter complier. Clothes no longer fit? You could throw them into a recycling bin, where they'd be torn apart molecule by molecule and reconstructed through nanotechnology into a new custom-designed outfit. On an industrial level, massive machines could print buildings out of diamond, and even whole artificial islands offshore.

At the time Stephenson was writing, 3D printing technology was in its infancy, but seemed to hold unlimited potential to create anything in the home. Also known as *additive manufacturing* — since it builds shapes by adding material layer by layer, rather than removing it through machining or creating it by injection molding — 3D printing theoretically has multiple advantages over traditional manufacturing. It can allow for the creation of complex geometries and an endless iteration of designs, leading to prototypes in mere hours rather than the days or weeks.

On the other hand, the building process can be excoriatingly slow, and therefore expensive, and limited materials and low resolution can result in substandard quality. In the more-than-three decades since it first appeared, additive manufacturing has remained a niche process, regulated to making cheap prototypes or jigs and fixtures to aid manufacturing rather than products themselves. As recently as 2016, *Inc.* magazine said the technology was “dying.”

The last five years, however, has seen an unlikely surge in new additive manufacturing technologies — many developed at MIT — and a crop of innovative companies, many like Desktop Metal based in the Boston area. “Small advances in the platforms that were developed 30 years ago are leading to absolutely huge changes in

“Thirty years ago, it was a zero billion dollar industry. When we got into this three and a half years ago, it was a $5 billion industry. Now it's a $9 billion industry. We think it's going to be 10 times bigger over the next decade.”



Ric Fulop
Founder & CEO,
Desktop Metal

"Small advances in the platforms that were developed 30 years ago are leading to absolutely huge changes in their viability as a manufacturing platform."

Jennifer Lewis
Hansjörg Wyss Professor of Biologically Inspired Engineering at Harvard University & Co-founder, Voxel8

Dayna Grayson
Partner, NEA

Richard D'Aveni
Bakala Professor of Strategy, Tuck School of Business at Dartmouth College

Chuck Hull
Co-Founder & Chief Technology Officer, 3D Systems

their viability as a manufacturing platform," says Jennifer Lewis, Hansjörg Wyss Professor of Biologically Inspired Engineering at Harvard University, and a co-founder of the additive manufacturing company Voxel8. "They are leading to higher surface finish, higher throughput, and faster build speeds."

That has finally put additive manufacturing on the cusp of being able to compete with more traditional technologies as a method for production, not just prototyping. Already, it's made inroads in industries such as aerospace, defense, jewelry, and medical and dental devices, all of which require specialized tools and equipment. From $9.8 billion in revenues last year, it is predicted by industry analyst Wohlers Associates to grow still more to $15.8 billion by 2020 and $35.6 billion by 2024. (While the company doesn't separate revenue for polymer and metal manufacturing, metal 3D printers represents over a third of all printer sales last year, $948 million out of $2.6 billion.)

The question, however, is whether additive manufacturing can grow out of specialized industries to gain wider adoption across manufacturing as a whole. "It is still less than 1 percent of most manufacturing markets, so getting to a tipping point is still far away," says Dayna Grayson, an engineer and investor with New Enterprise Associates (NEA). "The markets are so large, however, that by the time you get to 5 percent, you can build some very significantly sized companies."

Richard D'Aveni, a professor at Dartmouth's Tuck School of Business and author of the 2019 book *The Pan-Industrial Revolution*, predicts that in five to 10 years, additive manufacturing may well fundamentally change the way the world creates products. Rather than producing items in China and other countries overseas, companies like GE will be able to create its products in small, mostly automated factories all over the U.S., cutting down significantly on waste and shipping costs. Getting "over the chasm," however, will take effort and innovation. "The overall industry is at an inflection point, but it's stalled a bit," he says. "Moving into the next phase of mass manufacturing becomes a significant problem for almost every technology."

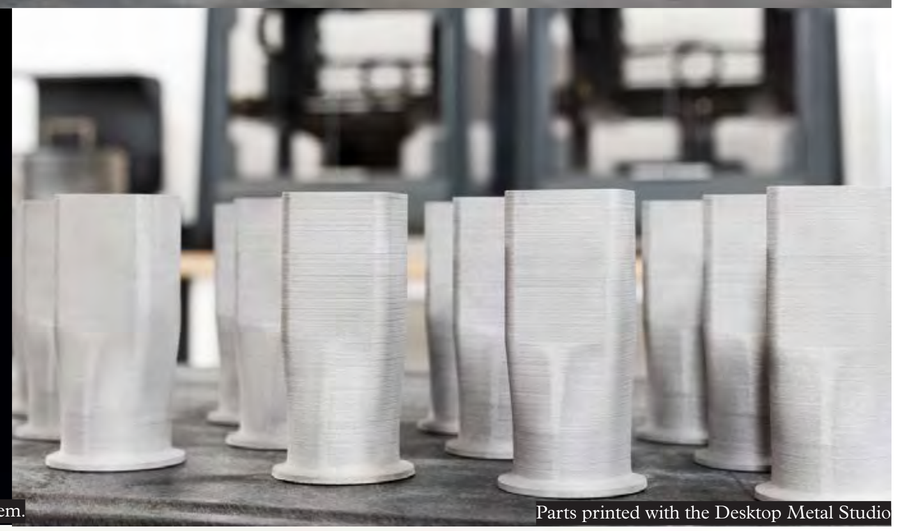
Polymers for Prototyping

3D printing was born in 1983, when engineer Chuck Hull dreamed of a quicker way to make prototyped parts. "At the time, you designed the parts on paper, a tool designer would design a tool, and then an injection molder would inject the plastic," he says. "It would take weeks and months, and if it didn't work, you had to do everything all over." At the time, he worked for Dupont on a process that used UV light to "cure" plastic photopolymers to put veneers on tabletops. He wondered if he could use the same process to make a three-dimensional object. "I thought to myself, these are really just thin sheets of paper — is there a way to combine all of these layers to make a prototype?" he says.

The machine he created consisted of a build platform submerged in a tank of resin, through which he shone a single-point UV laser to draw the shape for each layer. Once cured, the platform lifted slowly to allow a new layer of liquid to be cured. Eventually succeeding in creating a small eyewash cup, he called his invention a stereolithography apparatus (SLA), after the Greek words meaning "solid stone writing." In 1986, Hull formed the company 3D Systems, still one of the leaders in additive manufacturing

Desktop Metal production system.
Images courtesy of: Desktop Metal

A rendering of a part prior to printing. A component printed using the Desktop Metal system.



Parts printed with the Desktop Metal Studio

today. Over the years, the company has refined its original process, which still mostly focuses on prototyping, but has ventured into some manufacturing as well.

In 1998, for example, the company Align began using 3D Systems' printers to create their progressive set of dental aligners for adults as an alternative to braces. Made from biocompatible polyurethane resin, the products take advantage of the rapid customization to design the device for an individual patient's mouth. More recently, surgeons have used the company's printers to make surgery guides to help them make incisions in the right place. "When I step back and look at all of the progress that has gone on, it's become a pretty amazing invention," says Hull about his legacy.

The advantage of SLA is its high degree of resolution. Its downsides include the slow speed of the process, and the narrow range of materials usable through photopolymerization. In addition, because the layers are built up one after another, it can lead to some "shale-like" weaknesses in the strength of the final product. The company aimed to address those limitations in its latest printer, released last year. Called Figure 4, after a figure in Hull's original patent, it is designed for speed, with a newly designed range of polymers and release membranes so the layers peel off more quickly, as well as a separate UV curing station to finish the process and increase strength.

SLA isn't the only type of 3D printing technology, however. Shortly after its invention, University of Texas-Austin grad student Carl Deckard used a different approach, taking a bed of powdered resin and using a laser to heat and fuse the granules together. Known as Selective Laser Sintering (SLS), the technology was commercialized in the 1990s, and eventually sold to 3D Systems, which uses it alongside SLA. Another company, Arcam, developed a similar process using an electron beam; it was acquired by GE in 2016. SLS has the advantage of being able to produce stronger products out of plastic, nylon, and metal, but is even slower and more expensive than SLA, and similarly limited in materials.

The most common type of 3D printing first appeared in 1989, designed by mechanical engineer Scott Crump of Minnesota. Looking to create a toy frog for his daughter, he took a hot glue gun and filled it with a mixture of polyurethane and candle wax, extruding a thin stream of heated material that stiffened as it cooled. Continuing to experiment with the technology, which he called Fused Deposition Modeling (FDM), he and his wife Lisa formed the company Stratasys, which has since grown to become the world's largest 3D printing company, with more than $650 million in annual revenues.

Boeing, for example, says it saves $3 million for each 787 Dreamliner by 3D printing some 50,000 parts per plane.

Its printers use heated extrusion nozzles to squeeze out softened plastic filaments like a tube of toothpaste, laid down in layers to build up an object. The process is easy to use and faster than SLA or SLS, and allows for a much wider range of materials; however, does not have as high resolution, and is still not often cost-effective for mass production. Nevertheless, Stratasys has used it successfully to produce tools and prototypes for some 18,000 customers, including Airbus, Boeing, Lockheed Martin, NASA, Ford, and Volvo. Some have used it for specialized production parts, particularly in aerospace. Boeing, for example, says it saves $3 million for each 787 Dreamliner by 3D printing some 50,000 parts per plane.

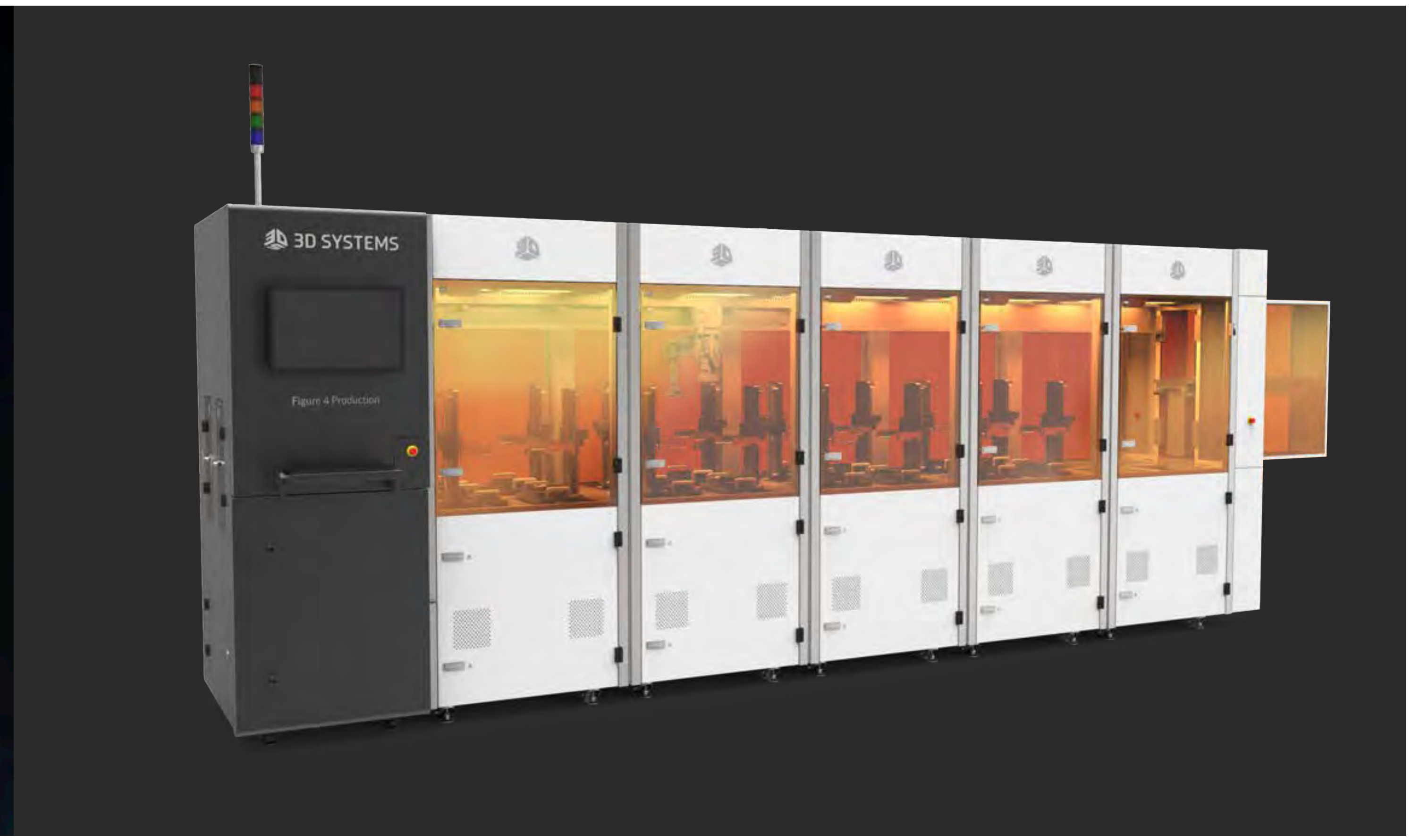
Rise and Fall and Rise

Led by the popularity of FDM systems, the future looked bright for additive manufacturing by the mid-2000s, with the technology seemingly poised to go mainstream. Enter MakerBot, a compact 3D printer designed by a former art teacher–turned-entrepreneur Bre Pettis, who envisioned a 3D printer in every home, like a sci-fi matter compiler come to life. Pettis appeared on the cover of WIRED magazine in October 2012 confidently holding MakerBot's Replicator 2 printer, with the bright orange coverline, "This machine will change the world."

By then, the company had already sold more than 5,000 early versions of his machine to an enthusiastic crowd of hackers and DIY artists. Other companies such as PrintrBot and Solidoodle raced to join in the frenzy; 3D Systems created its own consumer system called The Cube; and in 2014, Stratasys acquired MakerBot itself for more than $400 million. The printers soon disappointed consumers, however, with constant hardware problems and clogged extruder nozzles. More crucially, it turned out most people simply weren't interested in paying a premium price of $1,000 or more for a machine to print cheap plastic items at home.

Stocks that had risen 10-or 20- fold between 2009 and 2014 suddenly crashed back down to earth. (3D Systems went from $5 to $96 before dropping down to $9; Stratasys surged from $12 to $125 and back down to $16.) Publications and analysts that had been touting 3D printing as the next revolution were now declaring it dead. "There was a simplistic view that people were going to make things at home," says Max Lobovsky, who watched MakerBot's rise and fall as a grad student at MIT. "But of all the things we have at home, only a fraction can be made with any one 3D printer."

Even so, Lobovsky had personally benefitted from using 3D printers in digital fabrication workspaces at the MIT Media Lab, and wasn't ready to declare the technology "over." As he



(Left) Chuck Hull (Middle) A component printed by 3D Systems
(Right) The 3D Systems production system
Images courtesy of: 3D Systems

Printing components with a Formlabs printer.
Images courtesy of: Formlabs

A sample of materials, shapes, and sizes possible with a Formlabs printer.

finished his master's degree in 2011, he got together with two other MIT students to explore a new idea for a desktop printer. Instead of using FDM, it would use SLA, a technology that had been more or less passed over for personal use. "When we started, it only existed in these very large machines," Lobovsky says.

Lobovsky and his colleagues created a new technique that inverted the usual SLA process, so only a small tank of resin was needed. They used a laser from Blu-Ray players, creating a special software to calibrate it. Launching their company as Formlabs in Somerville, Mass., in 2017, they advertised their new machines on Kickstarter, with a price tag of just over $3,000. Instead of targeting home consumers, Formlabs aimed for small companies and independent craftspeople — so called "prosumers," who might not be able to afford a $50,000 machine from 3D Systems or Stratasys.

The Kickstarter campaign made $3 million in preorders, and has been in the black ever since. Its success has attracted over $100 million in investment from the likes of Foundry Group, Autodesk, and former GE CEO Jeff Immelt, now a venture partner at NEA, earning Formlabs a $1 billion valuation by last August. The company now has 600 employees worldwide, and is already looking to hire more. With a build size of about 5 ½ x 5 ½ x 7 inches, Formlab's sweet spot is in prototyping and molds. Its technology, for example, can print patterns in heat-resistant plastic used by jewelers as molds for metal, as well as molds for custom-designed dental liners and hearing aids. Last October, Formlabs announced a partnership with Gillette to create custom-designed razor blade handles, with 48 designs in 7 colors, under the tagline, "a man's grooming tools should be as unique as he is."

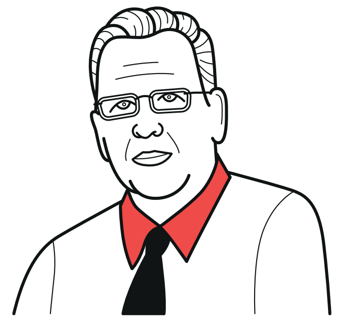
Aside from molds and mass customization, however, SLA has also gotten a second look as a mass-manufacturing technology. One of the most promising new additive manufacturing companies, the Redwood City–based Carbon, started with a similar concept to stereolithography, but rather than building an object painstakingly layer by layer, it envisioned a rapid, continuous process. "We wondered if we could grow parts out of a puddle, like the T-1000 in the *Terminator* movie," says Carbon founder Joe DeSimone, a University of North Carolina chemistry professor and winner of the Lemelson-MIT prize in 2008, referring to actor Robert Patrick's character famously emerging out of a pool of mercury-like liquid in 1991 film *Terminator 2: Judgment Day.* "In other words, could the mass of an object be derived from a source of liquid resin below it?"

The technique he developed, called continuous liquid interface production (CLIP) uses a special window that controls the flow of both light and oxygen to allow photopolymer resin to solidify on an inverted build plate that moves slowly upward from a pool of liquid. "This enables the generation of a continual liquid interface," says DeSimone, "and thus the ability to rapidly grow layerless parts." The process allows the UV light to flash a pattern all at once, rather than drawing it with a laser, allowing parts to be built 25 times faster than previous SLA processes with less waste and a smoother finish. It also makes parts stronger, since they don't have the same shale-layer effects of traditional SLA. "With our materials, we are able to achieve parts with properties that compare to injection molded parts," DeSimone says. The company has designed resins for silicones, polyurethanes, elastomeric polyurethanes, and rigid high-temperature materials such as epoxies.

Founded in 2013, the company raised nearly $700 million by late last year, both from VCs such as Baille Gifford and ARCHina Capital; and companies including GE, Johnson & Johnson, and Adidas. It crossed the $1 billion valuation threshold last year (making it the third additive manufacturing "unicorn" along with Desktop Metal and Formlabs), and as of June, reached $2.4 billion. Starting in 2017, Adidas began using Carbon's technology to create plastic cushioned midsoles for its Futurecraft running shoes for the consumer market. More recently, Carbon has revealed a larger printer called the L1, with a build volume 10 times that of its previous printer. Sports equipment company Riddell has used the technology to make custom-designed football helmet liners for NFL players, using some 140,000 individual struts, printed in two materials at once. "Certain areas of the liner function differently than other areas in order to optimize energy management in the event of an impact," DeSimone says. Ridell plans on releasing the helmets to the consumer market late this year or early next year.

Another company, Fortify, also uses a projector rather than a laser to polymerize plastics, but rather than build the structure continuously, it creates it layer by layer, a technique called Digital Light Processing (DLP). Created by Josh Martin and Randall Erb at Northeastern University, Fortify also integrates electromagnets into the printing process it calls FluxPrint, which can control the orientation of fibers embedded in photopolymeric resins to give the structure added strength, stiffness, or thermal conductivity. "It's very programmable and wireless in nature," says Martin, who co-founded the company Fortify, based in South Boston, in 2016. "We can pretty precisely control these additives without needing to use a large energy potential."

Max Lobovsky
Co-Founder & CEO,
Formlabs



Joe DeSimone
Co-Founder & CEO,
Carbon

Josh Martin
Co-Founder & CEO,
Fortify

"We wondered if we could grow parts out of a puddle, like the T-1000 in the* Terminator *movie," says Carbon founder Joe DeSimone. "In other words, could the mass of an object be derived from a source of liquid resin below it?"

The Carbon production environment.
Image courtesy of: Carbon

> ***Los Angeles-based company Relativity Space is working to create the first entirely 3D printed rocket. The company uses a massive FDM printer with 18-foot robotic arms to deposit melted metal wire on a spinning turntable to make round parts such as fuel tanks.***

By changing the magnetic fields during printing, the company can selectively polymerize different areas, building up materials with unique properties, voxel by voxel. For example, Fortify has used its magnetic 3D printers to produce electrical connectors for electric vehicles — complicated structures that need to be embedded with RF (radio frequency) properties, at the same time withstanding high temperatures beneath the hood. “To make those with tooling processes is super-expensive,” he says. In addition, the company has been able to make high-performance plastic tools for injection molding. “The 3D printing space has been trying to crack this for decades, and they have not been able to perform under high levels of pressure,” Martin says. “We can take a process that would usually require three months, and turn it around in a week or less.”

Expanding to Metal

While additive manufacturing originally used plastic polymers, one of the major innovations has been the adaptation to metals. German firm EOS first commercialized a technology called Direct Metal Laser Sintering (DMLS) in 1995, a variation on SLS that shoots a high-wattage laser into a bed of powdered metal. The process allows for precision parts with complex geometries, even though it can be slow and expensive, with a single part costing anywhere from $500 to $2,000 to make. For that reason, the process has made the most inroads in the aerospace industry; GE has used it to print parts for jet engines, and SpaceX and Virgin Galactic have used it to create parts for their rockets.

Los Angeles-based company Relativity Space is working to create the first entirely 3D printed rocket, raising $145 million this October from Bond and Tribe Capital, bringing its total investment up to $185 million. The company uses a massive FDM printer with 18-foot robotic arms to deposit melted metal wire on a spinning turntable to make round parts such as fuel tanks. The company, which was founded in 2015, plans on launching its first rocket in 2021. With a payload of up to 1,250 kilograms, the rocket is designed to use 100 times fewer parts than traditional rockets (1,000 compared to 100,000), and be constructed in just 60 days rather than several years.

Recently, other companies such as Desktop Metal have taken metal printing’s success in aerospace and introduced new processes to bring down cost for other industries as well. Rather than use heat to fuse metal wire or powder, Desktop Metal uses a process invented by MIT professor and co-founder Ely Sachs to fix powder with an adhesive binder instead. Past a series of protective doors in Desktop Metal’s factory, row upon row of mini fridge–sized machines whir productively. Each has a pair of mechanical arms that pushes sticks of wax and metal powder through a nozzle, similar to FDM, building up objects layer by layer on a build plate. When they are done, a technician will place the objects in a debinder where a liquid solution will remove the wax, creating open channels inside the object. Then it is put into a hot furnace where the metal shape will be sintered, hardening as it shrinks by up to 20 percent. At the same time, the sintering bonds the metal from all directions, fusing the layers together to increase overall strength.

The process, which the company calls its Studio System, began shipping in June to companies including Ford, Stanley Black & Decker, Goodyear, and Owens Corning, which use it to create prototypes, molds, jigs, and fixtures to help their manufacturing process, says VP of Product Larry Lyons. In addition, he says, vehicle companies including BMW and Caterpillar are using it to print spare parts on demand. “Caterpillar has a 40-year guarantee on spare parts,” he says. “So

Products, components, and tools showcasing the diverse materials and properties possible with the Carbon printing system.
Images courtesy of: Carbon

they just have these massive warehouses all over the world filled with parts they might ship out once a month." By printing parts on demand, they can dramatically lower costs for consumers, who could have a part made right at the dealership.

Through another set of doors is Desktop Metal's much larger Production System, which uses a different process called Binder Jetting. Large machines drop a thin layer of powder on a build plate, then a print head runs over it, dropping binder layer by layer, allowing for exquisite resolution of detail at 100 times the speed of SLS. When printing is done, workers in white hazmat "rabbit suits" remove excess powder, which can be recycled. The system can be used to create dozens of parts at once, all fired together in an industrial-sized furnace, resulting in the company's 20-times cost savings. The company plans to start shipping its first systems by the end of the year.

Desktop Metal isn't the only company in the Boston area to pioneer metal manufacturing, however. In nearby Watertown, Markforged was founded by engineer Greg Mark as a one-stop shop for 3D printing, employing a range of technologies and materials. Among them is its new Metal X printer, which uses a system similar to Desktop Metal's Studio System to lay down metal powder encased in plastic binder into 3D shapes that are then hardened through sintering. The company has raised $137 million to date, from the likes of Matrix Partners, Summit Partners, Microsoft, and Porsche.

"If you were an alien coming down from space and had never seen 3D printing before, you would say that this is objectively the technology everyone should bet on," says Davide Marini, CEO of Inkbit

While binder jetting can increase speed for metal production, it does have its drawbacks. As sintering shrinks products, it can create very slight variation between them. While software can compensate for that variation to an extraordinary degree, there may still be a 3 percent range of variability. While that isn't a problem for small objects, issues obviously increase with size.

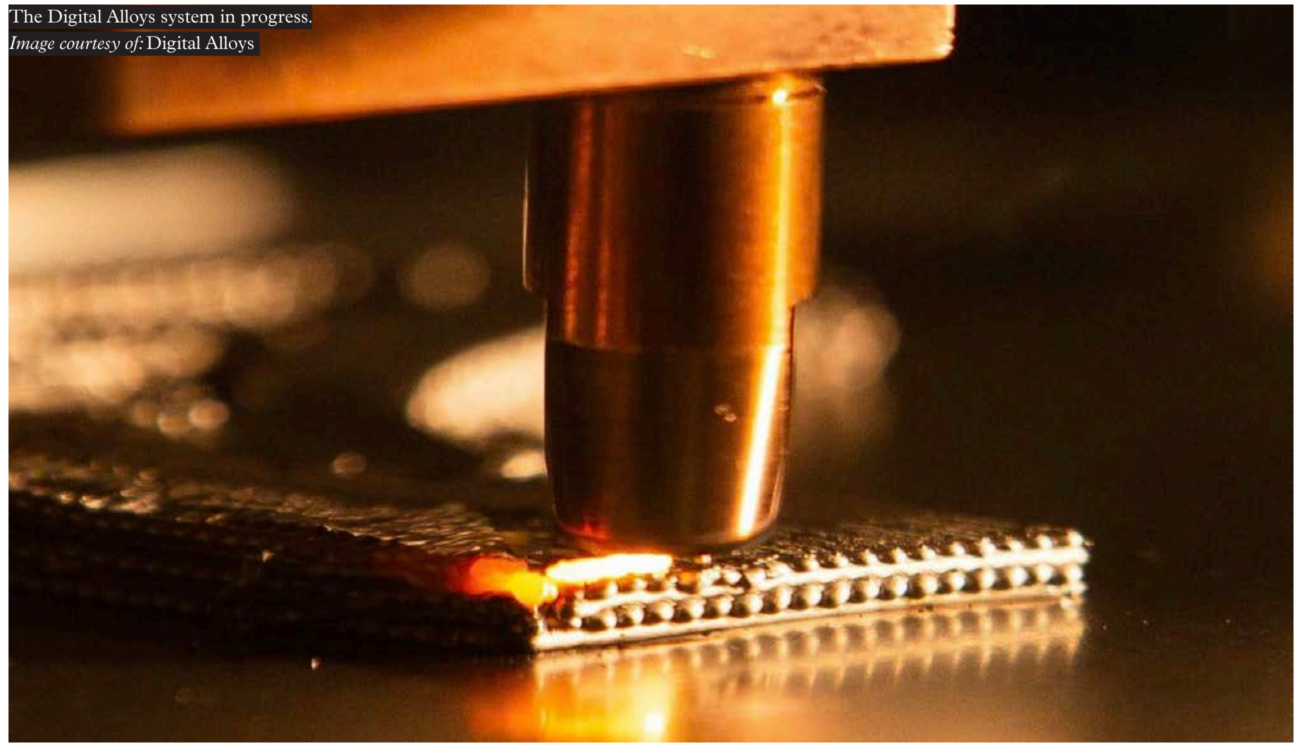
Down the street from Desktop Metal in Burlington, startup Digital Alloys has been using a different method for metal printing that allows for larger sizes. Similar to FDM, it starts by extruding a metal filament through a nozzle. However, rather than using heat to melt the metal, it sends an electric current through the wire, liquefying it just at the point of contact. "It's the same physics that heats a coil in a toaster," says company CEO Duncan McCallum, a mechanical engineering graduate from MIT and longtime venture capitalist, who co-founded the company in 2017. Called "joule printing," the process creates less waste than machining, and can build layers quickly, without the need for sintering. The company says it sees "full material fusion" between layers, creating a density of 99.5 percent and a tensile strength stronger than cast metal, comparable to wrought metal. "We're low-cost, the quality is exceptional, and we get a very dense metal right off the printer," McCallum says.

Duncan McCallum
CEO, Digital Alloys

It terms of cost, the company's sweet spot, says McCallum, are objects "larger than a tennis ball, but smaller than a beach ball." For those parts, he says, "we can do it faster and cheaper than any other solution we're aware of." (The process doesn't currently have high enough resolution for smaller objects, but could scale to larger objects with a larger printer.) A titanium fuselage bracket for aerospace, for example, uses 90 percent less material and can be made in 70 percent of the time, cutting costs by 60 percent — from $980 to $385. So far, the company has been producing parts in-house for clients including Boeing and Ford. It plans to sell its printers to companies starting in 2021. "First we're building the cookbook," McCallum says, "then we plan to give the cookbook to others."

Widening the Scope

One of the most difficult challenges in additive manufacturing is how to print with several colors or materials at once. One of the newest entrants into the 3D printing space, HP, has taken some steps to solve that problem with a technology called Multi-Jet Fusion (MJF), developed in 2015. A sort of cousin of SLS, MJF starts with a bed of polymer powder. However, instead of shooting it with a laser, the printer heats the entire bed almost to its melting point, and then passes a print head over the area with thousands of small nozzles that deposit an infrared-sensitive ink. When a high-power infrared energy source passes over the same area, it fuses it to the powder underneath. Some 10 times faster than SLS and half as expensive, the process also allows printing in several different colors at once, with the ability to control down to individual voxels (the 3D equivalent of pixels). The technology can be used to print multi-color prototypes, as well as objects such as custom-designed cell phone cases.



The Digital Alloys system in progress.
Image courtesy of: Digital Alloys

Another technology that uses a similar technique is called Material Jetting (MJ). Created by PolyJet in 1999, and since acquired by Stratasys, it forgoes the messy powder bed to print droplets of ink directly onto the print bed. The drops are either heated, setting as they cool, or subjected to a UV light to cure them, similar to SLA. The process is fast, relatively clean, and allows for control not only of colors, but also of the materials themselves, able to mix different types of polymers on the fly for different voxels. Stratasys' J750 machine, for example, can print in six different materials with hundreds of thousands of color options, and has been used to print anatomical models.

"If you were an alien coming down from space and had never seen 3D printing before, you would say that this is objectively the technology everyone should bet on," says Davide Marini, CEO of Inkbit, a company based in Medford, Mass., that also uses material jetting. There are two problems, however: Any material too viscous will clog the tiny nozzles (5 to 15 microns wide), limiting materials. Second, random variations in the ways the nozzles spray the ink lead to imperfections as layers build. To compensate, Stratasys' J750 machine sweeps a scraper across the surface between layers; however, that slows the process and further limits the materials, since anything too sticky, such as epoxies, will cling to it.

Marini studied mechanical engineering in Milan and worked as an investment banker in London before coming to MIT to study biomaterials. There, he learned of new technology being developed by MIT scientist Wojciech Matusik at the Computer Science and Artificial Intelligence Laboratory (CSAIL) to address the limitations in MJ. He developed chemicals that would be liquid enough to shoot easily from the nozzles, but then change when exposed to UV light, to create more complex materials such as epoxies. In addition, he developed an ingenious system to cut down on errors using machine vision and artificial intelligence.

As ink is laid on the object, a lens scans it at high resolution to find any random errors. The print head then automatically compensates when laying down the next layer, placing more or less ink in spots to make the surface flat, obviating the need for a scraper. "We can scan at resolution of 20 microns without any change to speed," says Marini, who spun the company out of MIT in 2017 with Matusik and funding from Italian packaging company IMA.

Inkbit has since formed a partnership with Johnson & Johnson to create products such as medical devices combining multiple materials at high resolution. One device, for example, features tiny channels of less than a ½ millimeter in size. With the speeds possible, an intricate plastic device that would cost $350 using SLA could be produced at the cost of only a few dollars, Marini says. Next, the company plans on installing several beta machines at partner companies to continue to test the technology before releasing it more widely.

The possibilities for multiple materials go beyond combining polymers. At Harvard, Jennifer Lewis' lab uses a technique similar to material jetting, but using a pneumatic system to extrude a paste-like ink through larger nozzles at room temperature, allowing for a much wider range of materials. At the Wyss Institute, Lewis has been a pioneer in printing 3D artificial organs with living cells. On the manufacturing side, however, she helped found the company Voxel8, which uses a method called ActiveMix to build complex products.

One of the company's main projects is 3D printing shoes. Unlike SLA processes used to print midsoles, Voxel8 is focusing on the fabric upper sole of the shoe, using its technology to embed polyurethane inks into the fabric. "We can take a piece of textile and screen print all of these zonal features and patterns, both for aesthetics and also functional purposes," says Lewis. For example, by the way material is printed, the printer could make parts of the shoe stiffer than others. Currently, she says, the company is working with two of the top five athletic footwear companies to develop mass-customized shoes.

Lewis and her colleagues have also used the system to embed electronic components, such as sensors and batteries, into fabrics to create wearable electronics. "You name it, we have printed almost every class of functional material you can imagine, and we have print heads that can switch and mix on demand." While many of these methods are still under development, Lewis believes it is only a matter of time before more manufactured products embrace the capabilities of 3D printing — not only to replace their current manufacturing techniques, but to allow for creation of new forms and materials not possible any other way.

"I'm not so much a believer in the idea that every home will have a 3D printer in 10 years, but the technology is penetrating evermore into companies' production platforms," Lewis says. "It's providing an opportunity to design new materials, voxel by voxel, in a way we've never been able to do before." We may never see the day in which some matter complier allows us to create everything we can possibly desire. But we may see a day — and soon — in which many different types of additive manufacturing technologies will combine to create significant parts of the objects we use, drive, and wear every day." +

Material World

In addition to new technology and machines, additive manufacturing will need a new class of high-quality materials if it is going to truly compete with traditional manufacturing techniques. As a doctoral student at Caltech, Raymond Weitekemp never intended to go into 3D printing. "I came into additive manufacturing kicking and screaming," he says. He'd seen the crash after MakerBot failed to live up to expectations, and was skeptical about the industry. Working to develop high-performance materials in the lab, however, he stumbled upon a new photosensitive polymer, when he used the wrong catalyst for a reaction. "I like to say I half-invented it," he says, "it was completely unexpected."

That polymer, which he called COR alpha (short for Cyclic Olefin Resin) turned out to be 10 times as rugged and durable as other photopolymers, and able to withstand high temperatures without losing strength. "In Izod impact tests, most people can do 10 to 30 joules per meter, but we can do 100 to 300," he says. In 2016, Weitekemp has since spun the technology into the Berkeley-based company, Polyspectra, whose sole purpose it to create new high-quality materials for additive manufacturing.

"Our first car took 44 hours to print...the next year, we made a car double the size in half the time." – Jay Rogers

Raymond Weitekemp
Founder & CEO,
polySpectra

Jay Rogers
Co-Founder & CEO,
Local Motors

Going Places

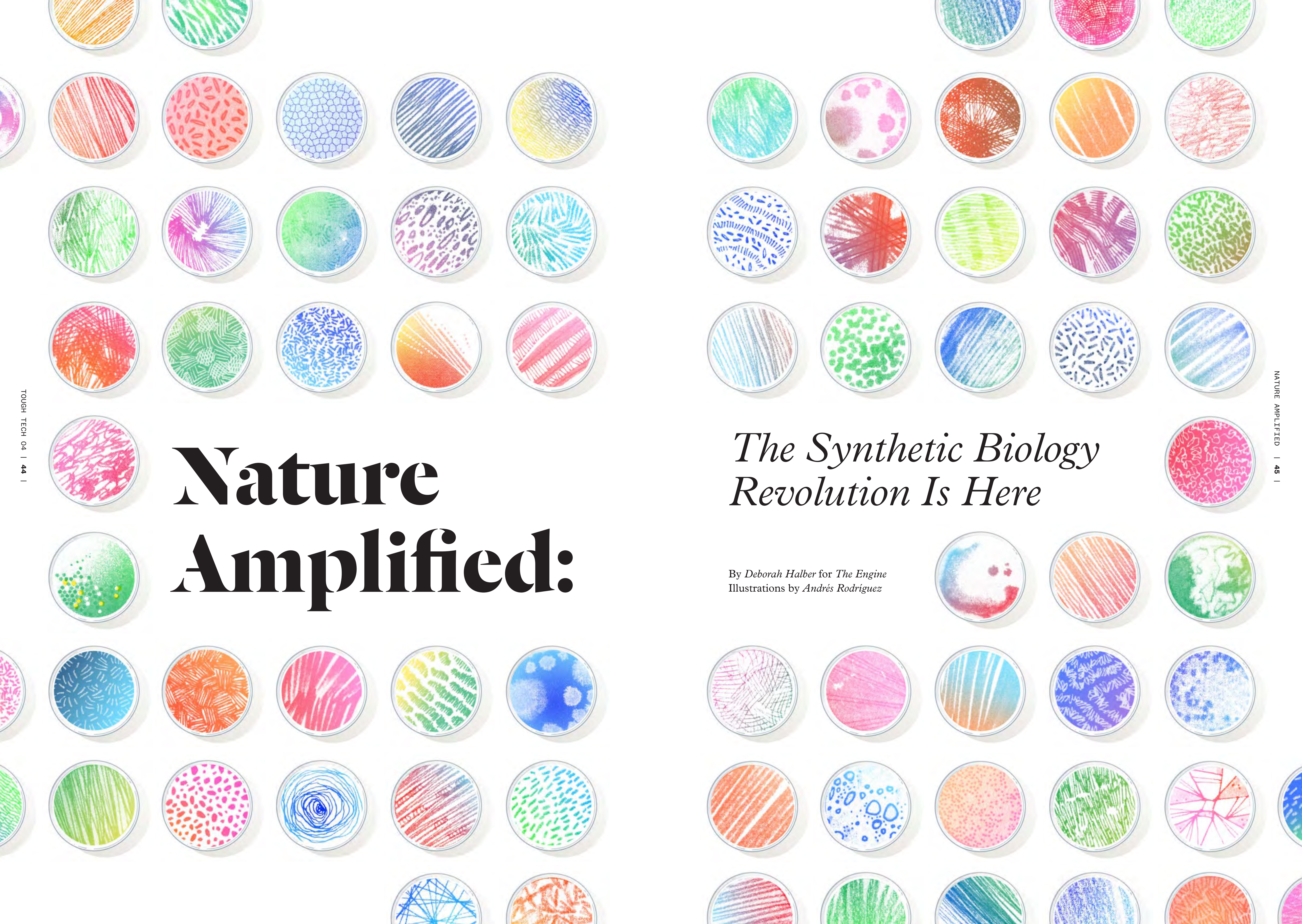
After specialty industries such as aerospace and medical and dental devices, the automobile industry may be the best hope for additive manufacturing breaking through to the mainstream. Already, companies including Ford, BMW, and Volkswagen have gone from using 3D printing for tools and prototypes to 3D printing their first parts for use in commercial vehicles. "Automobiles are the big bellwether that everyone is watching," says Tuck professor Richard D'Aveni. "So far, it's only making slight inroads, but it's marching towards wider use."

Meanwhile, one company isn't waiting for the rest of the industry to catch up. Arizona-based Local Motors has already started using additive manufacturing on a heroic scale to produce the world's first 3D-printed cars. The company is the brainchild of Jay Rogers, an Iraq war veteran who saw two friends killed during their deployments, due to outdated military vehicles. When he returned from overseas in 2006, he enrolled in Harvard Business School with the intent of creating a company to get new technology into military vehicles more quickly.

At the time, 3D printing was still a nascent technology for manufacturing, and Rogers' company was looking at rapid methods for laser cutting metal; but after he saw a demonstration of an SLS machine, he realized that cars could be printed more quickly and more durably using a polymer frame. Switching his focus to civilian use, Rogers founded Local Motors and used a giant FDM printer to lay multiple layers of carbon-fiber reinforced plastic to create a convertible buggy called Strati — the first 3D printed car — revealed at the Detroit Auto Show in 2014. "Our first car took 44 hours to print," he says. "That's not industrial speed. But the next year, we made a car double the size in half the time."

Since then, the company has created a larger shuttle bus called Olli, printed in two large parts — top and bottom — that are fitted together. While the other 2,000 parts of the car, including tires and electronics, are conventional, the bus is 90 percent 3D printed by volume. After exhaustive crash testing in which the frame was tooled for maximum safety, the company has sold the car commercially in 10 cities, where it operates on college, government, and assisted living campuses at speeds of up to 30 miles an hour. The company is still working its way through a thicket of laws to certify its cars for highway use, but Rogers eventually predicts that 3D printing will create cars that are both safer and cheaper than traditional vehicles. "It has nothing to do with the capability, and everything to do with regulation," Rogers says. "We believe the best way to show we can do it is to do it."

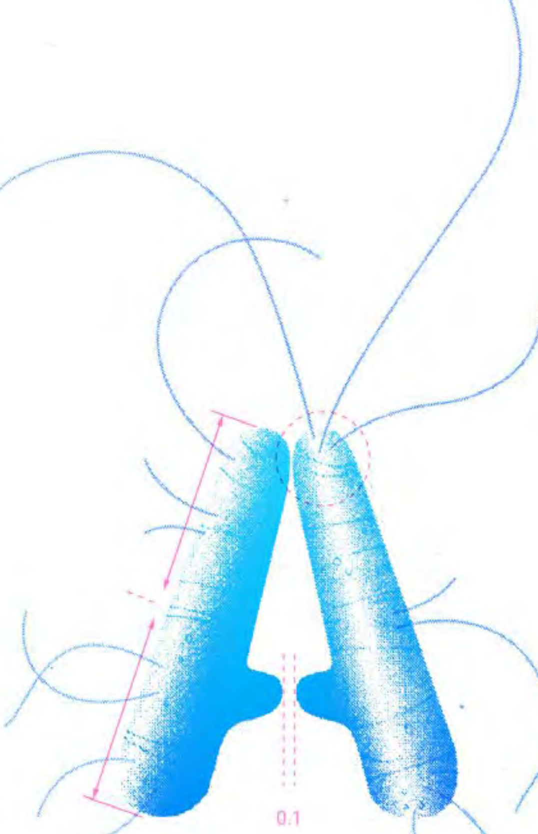
A 3D-printed Olli vehicle.
Image courtesy of: Local Motors



Nature Amplified:

The Synthetic Biology Revolution Is Here

By *Deborah Halber* for *The Engine*
Illustrations by *Andrés Rodríguez*



Ajikumar Parayil reaches inside what looks like a black plastic wardrobe, tears a leaf from a bushy plant and sniffs it. A geranium, he guesses.

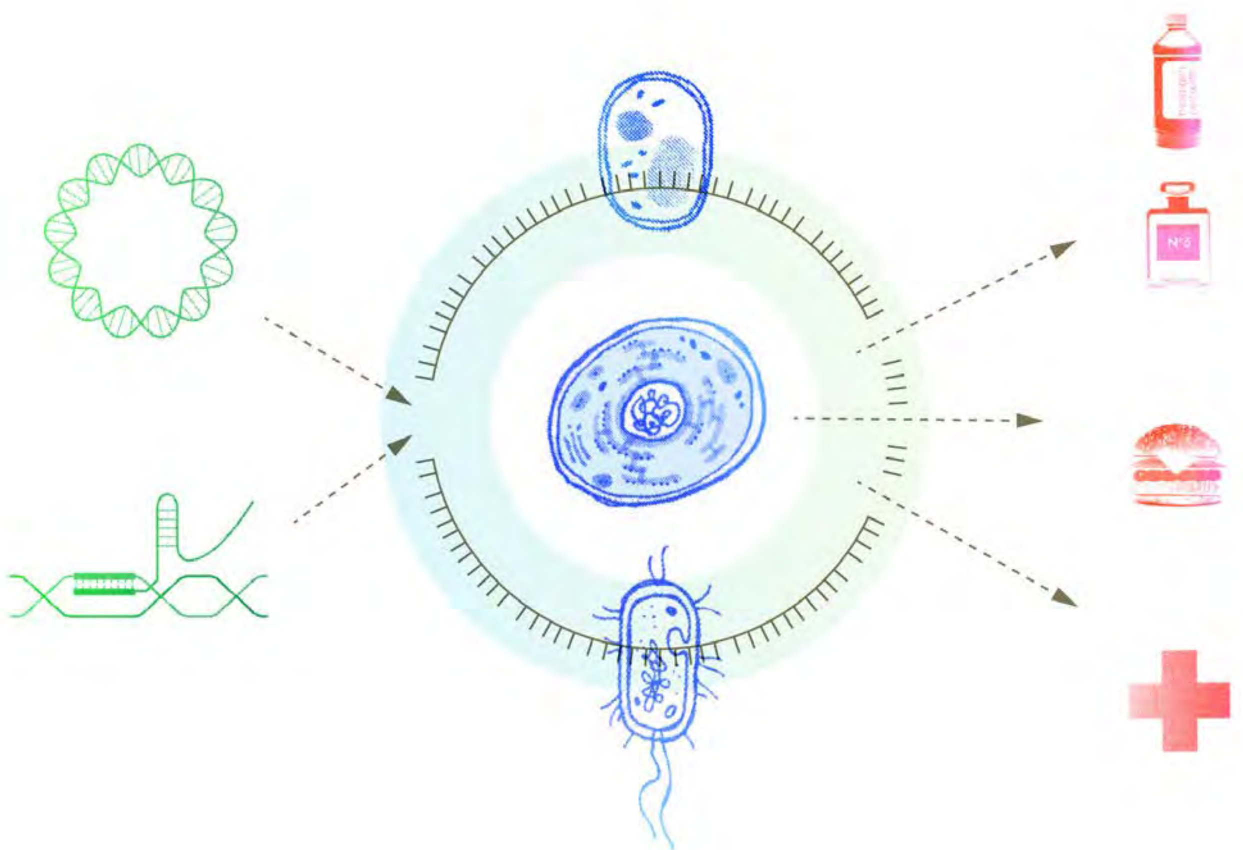
A chemical engineer and CEO, Parayil isn't too concerned with exactly which species grow in a mini-hothouse in Manus Bio's labs. His expertise lies in the molecular processes that let plants turn cheap, abundant resources into rare expensive chemicals such as essential oils.

Parayil's MIT spin-off seeks to do what plants can't — pump out large quantities of useful substances. By genetically programming fast-growing microbes to mimic the inner workings of plants, Manus Bio aims to mass-manufacture ingredients for new, cheaper, safer, more effective food and cosmetic ingredients, pharmaceuticals, and agricultural chemicals.

The global synthetic biology market is expected to surpass $55 billion by 2025. A dizzying array of potential applications stem from the notion that if nature can make a tiny amount of a pesticide or a healing agent, engineers can tweak nature to make a lot more. "Whatever you see biology in nature doing, we'd like to go in and harness that," says MIT biological engineer Chris Voigt. "Cells are the ultimate engineering substrate. We view living cells as systems that can be reprogrammed to do things they don't naturally do."

Synthetic biology startups and research labs are working on biofuels, biodegradable plastics, microbes engineered to seek and destroy cells that cause disease, environmentally friendly industrial solvents, a better artificial sweetener, a new nontoxic pesticide, and other products.

Many synthetic versions of plant products are based on petrochemicals. By manipulating genes and organisms to produce naturally occurring substances like nootkatone in grapefruit oil, Parayil and others hope to transform traditional, fossil-fuel-intensive chemical manufacturing — one of the world's worst polluters — into an environmentally friendly, sustainable industry.



Gee-Whiz Genetic Engineering

Synthetic biology sits at the juncture of biology and engineering. Its building blocks are genes, living cells — including human cells — and organisms such as yeast, fungi, and bacteria.

Putting organisms to work isn't new. For thousands of years, civilizations have used microorganisms to make alcoholic beverages, bread, and other products exploiting fermentation. It wasn't until DNA's structure was elucidated that biology proved open to manipulation at the genetic level.

University of Texas researcher Randall Hughes believes that if the 20th century was the century of the atom, the 21st century will be dubbed the century of DNA or, in Voigt's view, the century of genetic engineering.

Advances in sequencing and synthesizing DNA have led to "groundbreaking technologies for the design, assembly, and manipulation of DNA-encoded genes, materials, circuits, and metabolic pathways, which are allowing for an ever-greater manipulation of biological systems and even entire organisms," Hughes wrote in a 2017 overview of synthetic biology.

In the early 2000s, members of the MIT Synthetic Biology Working Group — a pioneering consortium of researchers in and around Cambridge — wanted to provide an overview of their nascent field for a lay audience. They hired a cartoonist who had worked on a popular Spider-Man video game to produce a 12-page comic book called *Adventures in Synthetic Biology.* It was taken seriously enough to be published in the prestigious journal *Nature* in 2005.

In *Adventures in Synthetic Biology*, a kid reaching for a neon-green, googly-eyed blob yells, "Check out that bacteria!" The boy is outfitted in goggles, cargo pants, a scuba shirt and boots suitable for walking on the moon — a mix of *Back to the Future* and *Raiders of the Lost Ark*. In a moment of gee-whiz science reminiscent of the 1950s, the boy exclaims, "Imagine what might become possible if they were working for us!"

Putting organisms to work isn't new. For thousands of years, civilizations have used microorganisms to make alcoholic beverages, bread, and other products exploiting fermentation. It wasn't until DNA's structure was elucidated that biology proved open to manipulation at the genetic level.

In the early 1970s, scientists cut genes out of a frog's DNA and inserted them into *E. coli*, a common gut bacterium. The microbe was able to translate the frog's genetic information into proteins. And when the microbe divided, it made new copies of the frog genes along with its own. It was a Frankenstein creation, a bacteria-frog hybrid.

Altering the sequence of DNA's four basic building blocks turned out to alter proteins, which altered an organism's behavior. By adding the gene for a desired product or ramping up expression of an existing gene, researchers found they could use living organisms such as yeast and bacteria as factories to churn out useful products.

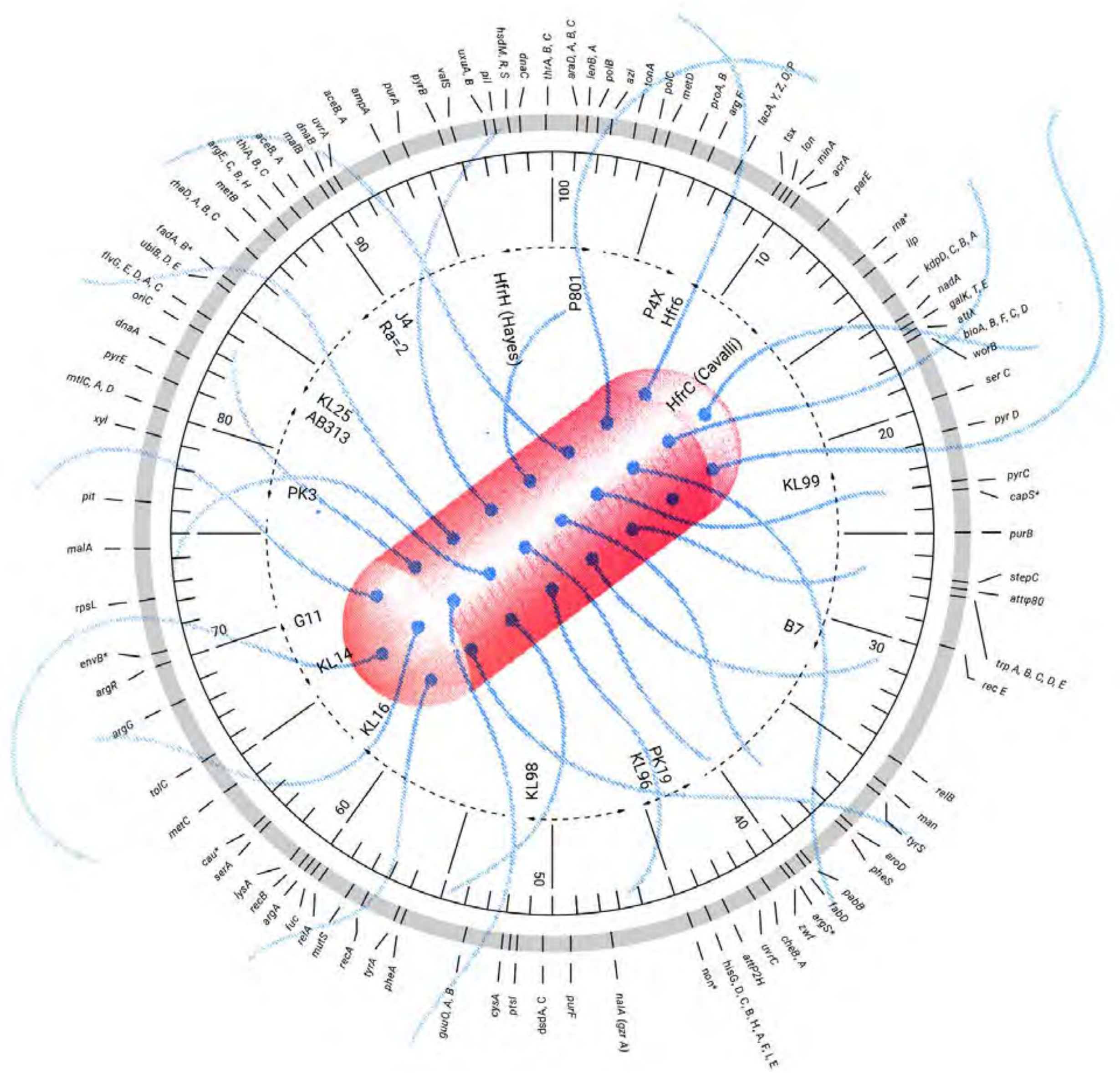
Synthetic biology sits at the juncture of biology and engineering. Its building blocks are genes, living cells — including human cells — and organisms such as yeast, fungi, and bacteria.

Adventures in Synthetic Biology
The MIT Synthetic Biology Working Group

Ajikumar Parayil
Founder & CEO, Manus Bio

Chris Voigt
Daniel I.C. Wang Professor of Advanced Biotechnology, MIT

Pamela Silver
Elliot T. and Onie H. Adams Professor of Biochemistry and Systems Biology, Harvard Medical School



With its relatively straightforward 4,000 genes, *E. coli* became the organism of choice to manipulate.

"Bacteria really are the powerhouses of molecular biology research, because their genes are much easier to modify in the lab and they can grow and evolve much more quickly than other organisms," says Pamela Silver, the Elliot T. and Onie H. Adams Professor of Biochemistry and Systems Biology at Harvard Medical School, whose lab works on reprogramming bacteria and other cells to perform a variety of new functions.

Within a decade of the landmark gene-splicing experiment, insulin and human growth hormone were being generated by genetically modified bacteria. One of the first biotechnology companies in 1971 promised that by 2000, virtually all diseases would be cured with proteins made through genetic engineering.

Fast forward to the early 2000s. Companies synthesized long fragments of DNA at a reasonable price, but researchers struggled to systematically engineer large-scale genetic systems. Even relatively simple organisms were too complex to predictably alter. The process was painstaking and labor-intensive, and largely hit-or-miss.

In the 18th century in New Haven, Conn., inventor Eli Whitney figured out how to mass-produce muskets — previously assembled painstakingly by hand — by using interchangeable parts. Early stages of synthetic biology at MIT revolved around a Registry of Standard Biological Parts: a library of well-characterized parts and modules that could be assembled in cells in different combinations, resulting in predictable outcomes.

With BioBricks created and submitted to the registry through an MIT-initiated global competition, student teams developed a bioengineering device that "prints" genetic circuits a water purification system , and a way to save the honeybees. In time, hyper-precise genome engineering tools such as CRISPR further expanded the scope of what's possible to coax cells to do for our own purposes.

In *Adventures in Synthetic Biology,* the kid thinks it would be fun to change the genome of the green blob so it blows up like a balloon. "First you

Images courtesy of: Ginkgo Bioworks

Barry Canton
Co-Founder and CTO,
Ginkgo Bioworks

Kristala Prather
Arthur D. Little Professor of
Chemical Engineering, MIT &
Co-founder, Kalion

need to assemble the DNA parts that encode your program," says a young woman in a white lab coat and oversized glasses, her hair pulled back in a messy bun. She hands him a thick blue book. "Get them from the catalog."

Foundries for Cells

In Ginkgo Bioworks' Bioworks3 foundry, a robotic arm systematically dips a thin black probe into tiny wells on a grid-patterned tray. It's doing what bench scientists do — inserting custom-designed DNA into cells — but it does it 24/7 at a higher level of output than humans could manage.

Ginkgo Bioworks designs genetic codes to build custom microorganisms. It was co-founded in 2008 by CEO Jason Kelly and three other former MIT biological engineering grad students, along with former MIT research scientist Tom Knight — at 68, considered the godfather of synthetic biology.

Knight, an electrical engineer and computer scientist who made the leap to biology in the 1990s, wanted biology to be more like engineering, where you could grab chips and other components off the bench, put them together, and have them work as expected. In a nod to semiconductor fabrication, Ginkgo calls its labs "foundries."

Working with partner companies, accelerators Y Combinator and Petri, and independent researchers, Ginkgo has reprogrammed cells to produce yeast that generates the fragrance of extinct flowers, bacteria that can decrease farmers' reliance on chemical fertilizers, and through its partnership with Cambridge, Mass., biotech firm Synlogic, so-called "living medicine." Synlogic and Ginkgo are developing a therapeutic that will break down toxic levels of the amino acid phenylalanine in the gut of patients with the metabolic disease phenylketonuria (PKU).

Yet Ginkgo is "application agnostic," says CTO Barry Canton. Its business model is to make synthetic biology itself cost-effective and accessible to any industry — especially ones that never imagined they could employ yeast, bacteria, or Chinese hamster ovary cells (used commercially to produce therapeutic proteins) to make products.

"There are a lot of heads of R&D at big companies who are trying to figure out how to make their development dollars go further and who understand — or are beginning to understand — the potential of synthetic biology," Canton says. "They're looking for cheaper ways to make existing products or how biology can make products that they can't make or buy via chemistry. And then they come and talk to us."

A Game of Whack-a-Mole

"There it is — the genome," Ms. Scientist tells the boy in the goggles as they soar past, a la The Magic School Bus, oversized corkscrews of blue and violet DNA. "The master program that's running the cell."

"So this is what we change to reprogram this critter?" the boy says. "Looks easy!"

At MIT, Kristala Prather designs new ways to engineer bacteria to synthesize drugs and biofuels. Prather, the Arthur D. Little Professor of Chemical Engineering, is co-founder of Kalion, a company commercializing the first microbial fermentation process to produce glucaric acid, a powerful biodegradable and nontoxic corrosion inhibitor.

Prather and her team were among the first to control how cells make chemicals relative to how they do their primary jobs: growing and reproducing. Prather's lab devised an internal switch that compels the cell to stop using all its ingested food for its own purposes and use it to make the product the researchers want it to make.

Prather says advances in computation, molecular and cell biology, data science, and machine learning have been game-changing for synthetic biology. And then there are the time-saving robotic lab workers, and software that models and simulates the function of new genetic circuits before they go near a petri dish.

But living cells are incredibly complex, dynamic systems. "As soon as you start adding a bunch of stuff, it changes how the rest of the system behaves in ways that can be very unpredictable," Prather says. It's like whack-a-mole: You push down on one part and another one pops up.

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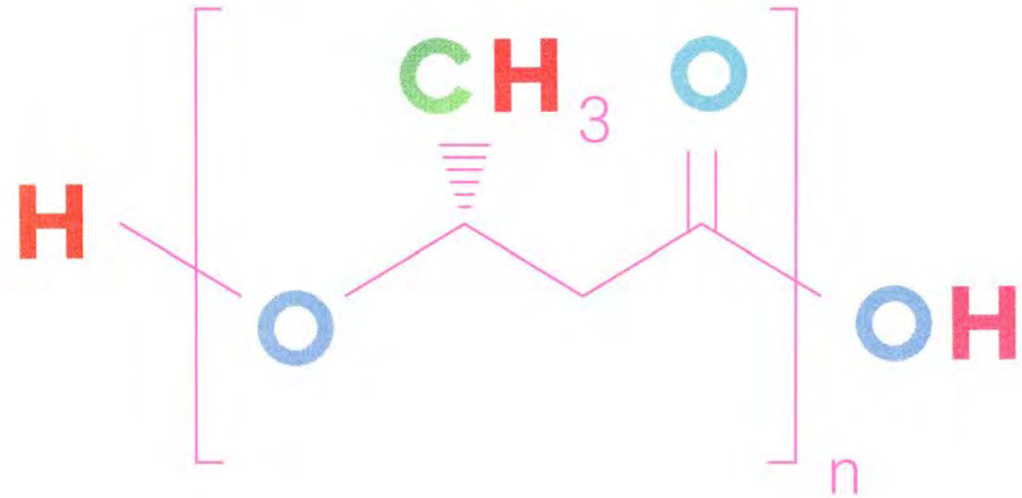


A polyhydroxyalkanoate.

At Ginkgo, Canton says that to get a cell to produce a specific substance or act in a desired way, "We have to come up with, let's say 10,000 different designs (of assembled strains of DNA). We need to manufacture all of those, test all of them.

"We have to come up with a new set of designs informed by that first round and go through that process again," he says. "And we need to do that multiple times for every project." Canton compares the resulting knowledge to Google's proprietary software. "Ginkgo accumulates code base in the form of enzymes, genes, entire strains that we've developed that we've shown to be productive," he says. The hope is that researchers will use that knowledge to piece together products to benefit people and rescue the planet, which is drowning in waste and struggling with an industrial base built around fossil fuels.

Better Bioplastics

A few years ago, bioplastics made from fermented corn seemed like great alternatives to petroleum-based plastics.

Shannon Nangle and Marika Ziesack aren't so sure. To break down commonly used bioplastics called polylactic acid, or PLA, you have to run an industrial composter containing a specific set of microbes at specific temperatures and durations. "Most composters don't even do that," Nangle says. "Few composters fully degrade PLA, so the PLA remnants end up in landfills and, like petrochemical plastics, they will not degrade. PLAs that find their way into the environment also will not degrade readily."

Public awareness of the millions of tons of plastic waste polluting the oceans is spurring governments to impose bans on single-use plastics. Consumer product companies are looking for alternatives. Nangle and Ziesack think they have a better one than PLA.

Nangle shows a visitor around the Harvard Medical School lab where she and Ziesack work as postdocs. A machine jiggles glass jars of bacteria growing in mixtures of gases. Ziesack, Nangle, and Pam Silver have engineered bacteria to produce a variety of compounds called polyhydroxyalkanoates (PHAs), a class of biodegradable, bio-based polymers. PHAs are promising, but have found limited applications in niche markets because of their high production costs.

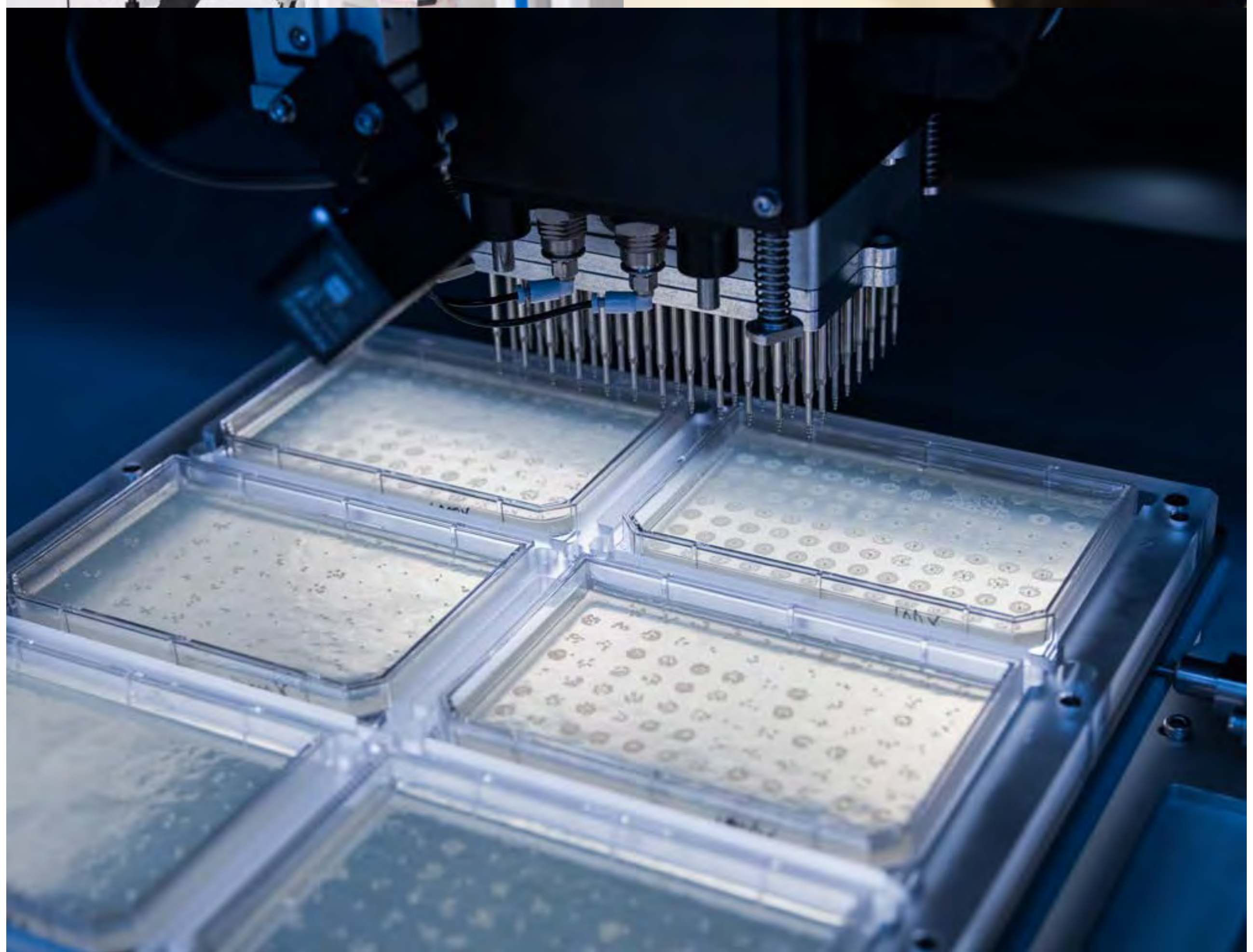
Unlike PLA, PHAs will degrade in the ocean and land, where they are a food source for local microbes. By diversifying and enhancing the existing range of PHAs, Nangle hopes to tailor PHAs to have similar properties to many types of petrochemical plastics.

Nangle and Ziesack have produced new varieties of PHAs directly from carbon dioxide and hydrogen by engineering the metabolic pathways of hydrogen-oxidizing bacteria called Knallgas bacteria — an accomplishment that could change the long-term sustainability of bioplastics.

"By using carbon dioxide waste

"Ginkgo accumulates code base in the form of enzymes, genes, entire strains that we've developed that we've shown to be productive," Canton says. Researchers will use that knowledge to piece together products to benefit people and rescue the planet.

Inside the Ginkgo Bioworks foundries.
Images courtesy of: Ginkgo Bioworks



streams instead of corn as input for our fermentation, we hope to scale up bioplastics production without competing for cropland," Ziesack says. The team is working to fine-tune these new bioplastics at a reasonable manufacturing cost.

From Cancer to Chemicals

In 2016, Gaurab Chakrabarti was in medical school, studying the role of chemicals in cancer progression.

Years earlier, a friend of Chakrabarti's from medical school had introduced him to Sean Hunt, who was pursuing a PhD at MIT in chemical engineering. "Sean would come down to Dallas," Chakrabarti recalled. "One night, we were playing poker and somehow we started talking about our research." That conversation would propel Hunt and Chakrabarti to Forbes' 2017 list of "30 Under 30" in manufacturing and industry.

Chakrabarti was looking at a protein that helps cells detoxify in the presence of quinones — toxic free radical byproducts of cell metabolism. In pancreatic cancer cells, clearing up quinones produces high levels of hydrogen peroxide, which cancer cells have evolved to withstand.

Chakrabarti told Hunt he had stumbled on a kind of super enzyme that efficiently turned sugar into hydrogen peroxide.

At MIT, Hunt was exploring ways to use nanoparticles to improve traditional methods of manufacturing hydrogen peroxide, an all-natural germicidal agent. The global market for hydrogen peroxide — used in electronics fabrication, water purification, agriculture, textile and paper pulp bleaching, plastics production, and rocket propulsion — is projected to reach $6.3 billion by 2026. Right now, it's expensive and environmentally unfriendly to produce.

At the time, Hunt was all about traditional chemical manufacturing. He considered enzymes — chemical reaction catalysts within a cell — too expensive and not very stable. "No, man," Chakrabarti told him. "Things have changed."

Capable of generating high concentrations of peroxide without losing effectiveness, the cancer cell enzyme worked far better than metal catalysts, which tended to degrade the peroxide at high concentrations. Now, Houston-based Solugen's bio-inspired reactions use enzymes derived from microorganisms that break down biodegradable, cheap plant material and turn them into hydrogen peroxide. Their process is cheaper and produces no harmful byproducts.

"We do water treatment, which is industry-agnostic. So we can be in upstream oil and gas-produced water, we can be in mining, agriculture, soil remediation," Hunt says. "The problems we're solving are all slightly different. But fundamentally, it's the same core chemical solutions."

In 2010, MIT chemical engineer Gregory Stephanopoulos and Parayil — a postdoc at the time — were hoping to find a way to induce bacteria to yield an intriguing substance called taxadiene isolated from the bark of the Pacific yew tree. A precursor of the potent anticancer drug Taxol, taxadiene was tricky to generate in quantity. Stephanopoulos and Parayil rejiggered *E.coli* to churn out one gram per liter — 15,000 times more than previously possible.

The researchers were investigating plant pathways that generated isoprenoids, an ancient and diverse set of metabolites that help plants do everything from make chlorophyll to germinate seeds. Industrial companies immediately saw the potential of this pathway "to alleviate a lot of their sourcing needs, particularly for natural ingredients," says Manus CTO Christine Santos, a graduate student in the lab who completed her PhD in 2010.

Manus' fermentation technology

> ***At the time, Hunt was all about traditional chemical manufacturing. He considered enzymes — chemical reaction catalysts within a cell — too expensive and not very stable. "No, man," Chakrabarti told him. "Things have changed."***

Marika Ziesack
Postdoctoral Researcher, Harvard University

Gaurab Chakrabarti
Co-Founder & CEO, Solugen

Sean Hunt
Co-Founder & CTO, Solugen

Christine Santos
CTO, Manus Bio

Alexander Titus
Head of Biotechnology, United States Department of Defense

In the not-too-distant future, synthetic biology may go beyond pairing an enzyme from a human cell with a structural protein from a yeast cell to create living systems unlike any existing organisms.

replicates how plants manufacture natural chemical compounds. "What we're doing is taking biosynthetic pathways that typically exist in plants and translating them into a microbial system," Santos says. "There's quite a bit of work that we do to optimize the performance of those enzymes, which have evolved in a very different cellular context."

Lately, the food industry has been abuzz about a substance found in the leaves of the stevia plant. Rebaudioside M or Reb M is sweeter than Reb A used in Truvia and other products. But it's trickier to extract.

Manus has engineered bacteria that mimic Reb M's metabolic pathway, and Manus' manufacturing facility in Augusta, Ga., is ramping up production of a zero-calorie sweetener based on Reb M. Among Manus' other products in various stages of development is a component of grapefruit oil that repels and kills mosquitoes, ticks, head lice and bedbugs. Unlike DEET, nootkatone is nontoxic. It's FDA-approved for citrus-flavored soft drinks and perfumes; the EPA may soon green-light it as a pesticide and insect repellent that could protect against Lyme disease, malaria, Zika, and more.

Safety on the Road Ahead

In *Adventures in Synthetic Biology*, the little dude sets to work making the googly-eyed green blob generate and trap hydrogen gas so it inflates like a party balloon.

To his delight, the blob starts to fill with hydrogen. Then it keeps going. It expands until it takes over the entire lab, pops and splats, flinging sickly green splotches everywhere.

"Hmm," muses the scientist. "Are you sure you understand enough about what you want to do? You don't want to make things worse."

As synthesis technology becomes cheaper and more widely available ("You can start a biotech company out of your dorm," Solugen's Hunt says) questions become increasingly worrisome: Who owns rewired organisms? What happens if they escape — or are inserted — into the wild? Could freely available DNA sequences of viruses or the genes encoding lethal substances such as anthrax become a threat to public safety?

Alexander Titus is assistant director for biotechnology in the Office of the Under Secretary of Defense for Research & Engineering. He's responsible for developing and overseeing the U.S. Department of Defense's biotechnology roadmap.

The U.S. bio-economy — economic activities based on renewable biological resources — emerged in the early 2000s, and its economic promise has ratcheted steadily upward. "In the future, we see biotechnology impacting nearly every aspect of business or technology," Titus says. The U.S. is already a world leader in the field, with 300-plus companies founded in 2017 alone.

"It will be a challenge to scale up critical biomanufacturing processes to realize the new class of manufacturing technologies," Titus says. "There are technical hurdles that need to be overcome to quickly and cost-effectively produce and isolate robust quantities of bio-based materials, molecules, and other products, as well as platforms that will need to be created in order to test and evaluate said products." Titus believes partnerships among industry, academia, and government will be key to leveraging existing resources.

Plus, he says, the DOD wants the U.S. to be a global biotech leader "so that we can help to ensure that biotechnology is used responsibly," he says.

Biosecurity and biosafety issues could hinder industry growth, Silver says. If technology relies on releasing organisms into the environment — such as through soil-dwelling microbes that boost crop yields — how do you ensure that doesn't get out of hand?

In the not-too-distant future, synthetic biology may go beyond pairing an enzyme from a human cell with a structural protein from a yeast cell to create living systems unlike any existing organisms. In April 2019, the Swiss Federal Institute of Technology announced that researchers there had created the world's first fully computer-generated genome of a living organism. While the organism itself does not yet exist, it's only a matter of time.

Harvard geneticist George Church and an international team of scientists have been working on "yeast 2.0," known as the synthetic yeast project— synthesizing a form of *S. cerevisiae* in which engineered chromosomes within a mostly intact original genome steer the organism to evolve along a desired path.

Silver, Church, and others founded a company called 64-x (64 minus x), which engineers organisms with entirely new genetic codes to function in otherwise inaccessible environments. These new life forms are immune — the company says — to "every virus on Earth." "Why we like them: These geniuses invented a new life form," wrote *TechCrunch* in August 2018.

Take the "living medicine" in development at Ginkgo Bioworks. CTO Barry Canton says the current goal is to engineer bacteria that help degrade harmful amino acids for those suffering from metabolic disorders. One day, the target product might be a much more extensively engineered cell that can sense — and respond to — changing disease conditions inside the body.

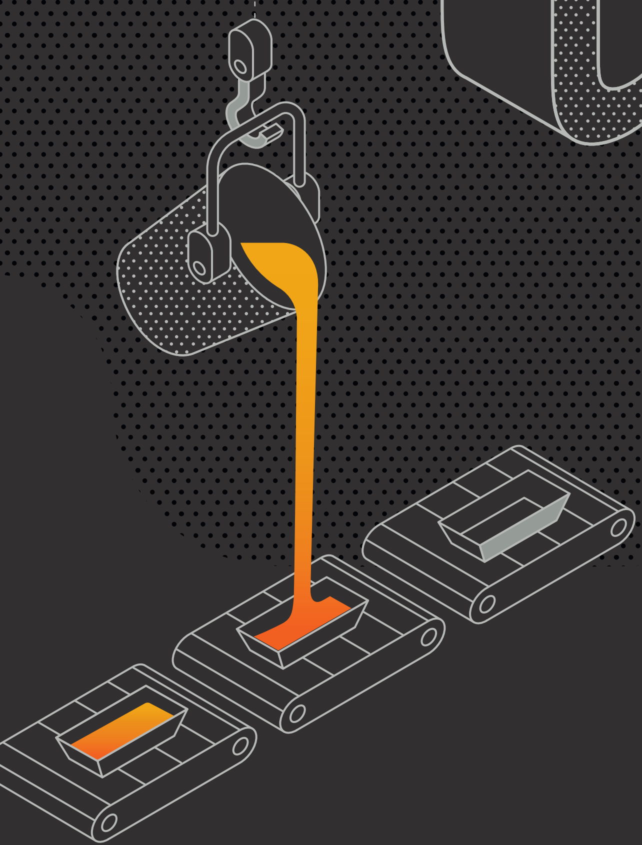
"We'll probably go through an evolution where you'll go from putting a handful of genes into a cell to totally redesigning almost every aspect of what the cell does," Canton says. "It will increasingly look like a specialized cell for making product X or treating disease Y. Today's relatively modest reprogramming of cells that exist in nature will, over time, create cells that are more pared down, more and more focused on the objective at hand." Such a cell, presumably, would no longer be a yeast cell or a bacterium, but something altogether different.

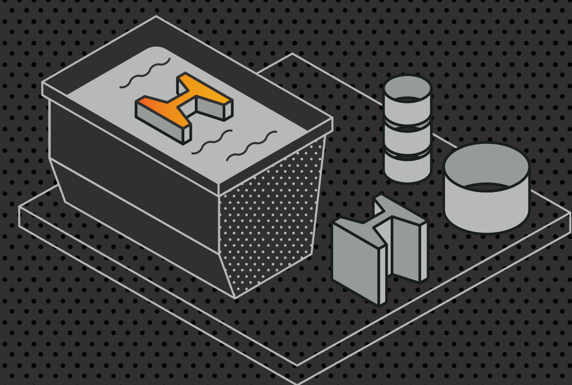
At the end of *Adventures in Synthetic Biology*, the scientist and the boy gaze, wide-eyed, as a perfect, smiley bacteria balloon floats gently off into the cosmos. "Look at us," the kid exclaims. "We're building stuff!" +

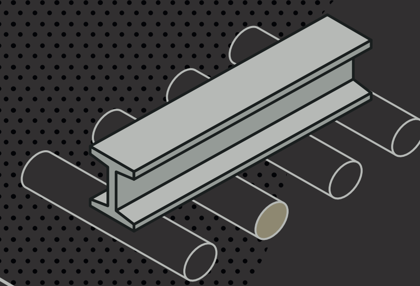
Images courtesy of: Ginkgo Bioworks

CLEANING UP STEEL

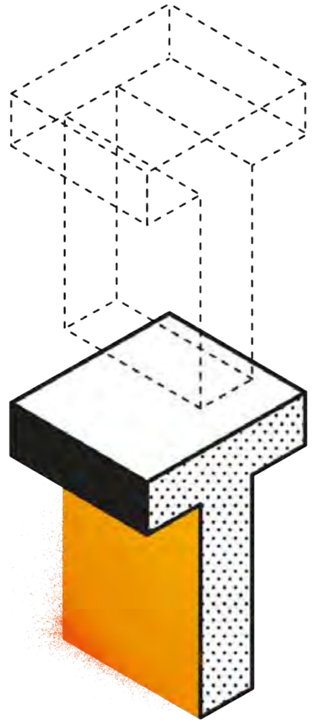
AND OTHER MATERIALS ESSENTIAL TO HUMANITY







By *Elizabeth Thomson* for *The Engine*
Illustrations by *Julie Carles*



The cars we drive, the buildings we live in, the processing and storage of the food we consume — these and much more are dependent on steel. The material is essential to humanity.

And we make a lot of it. In 2018, the world produced some 1.8 billion metric tons. That's enough to produce 43,100 copies of the Bird's Nest stadium in China, the primary venue of the 2008 Summer Olympics.[1] Plus, that demand is expected to grow as the Earth becomes more populated.[2]

Steel is also responsible, however, for huge amounts of carbon dioxide, the most important of the greenhouse gases that are slowly warming our planet and changing its climate.[3]

How huge?

Donald Sadoway, who has been a professor at MIT for 42 years, has created a new "country" to drive home the impact. "If you take the total carbon dioxide emissions of the world in 2018, and you break it down by country, the number one contributor is China," says the professor of materials science and engineering. "Number two is the United States. And if I took the total carbon dioxide emissions from the world steel industry, and compared them to all other countries, steel would rank third. So you have China, the U.S., and what I call The Republic of Steel."

In 2017, almost two tons of carbon dioxide were emitted for every ton of steel produced, making the industry responsible for "seven to nine percent of global direct emissions from the use of fossil fuels," according to the World Steel Association.[4] "That's big. *Big,*" says Sadoway, who notes that "close behind are cement and chemicals."

Bill Gates also recognizes the enormity of those numbers. "Whenever I hear an idea for what we can do to keep global warming in check … I always ask this question: 'What's your plan for steel?'," he wrote in his *GateNnotes* blog on August 27, 2019.[5] That question "opens the door to an important subject that deserves a lot more attention in any conversation about climate change. Making steel and other materials — such as cement, plastic, glass, aluminum, and paper — is the third biggest contributor of greenhouse gases, behind agriculture and making electricity."

Fortunately, many companies and researchers are reimagining the industrial processes behind our most polluting materials. They range from a company near Boston that's developing a way to make steel that replaces carbon dioxide emissions with oxygen, to MIT research on an electrically conducting cement with eco-friendly applications that could offset the material's negative impacts.

Toward Cleaner Steel

The steel industry is well aware of its product's impact on the environment and has been addressing the issue for some time. As a result, the North American industry in particular "has really made some significant gains over the last 30 years or so," said Mark Thimons, Vice President for Sustainability at the American Iron and Steel Institute (AISI). Since 1990, he says, "there's been a reduction in carbon dioxide emissions per ton of steel by about 37 percent."

Those cuts are due in part to a trend toward automation and toward reducing the number of steps involved in making steel. For example, says Thimons, those steps "used to include a lot of re-heating of steel, and that's been abandoned in large part in favor of continuous processing."

Recycling is also an "important part of the sustainability story for steel," Thimons says. More than 70 percent of the metal is recycled in the United States. And "any recycling improves the energy and emissions profile of the steel that's produced." Further, Thimons noted, unlike most other materials, steel can be continually recycled into other products without real loss of quality. A steel beam could become a car door or a vegetable can or a refrigerator, and vice versa.

The steel industry is also working toward future technologies that could make the steel making process more sustainable. Michael Sortwell is AISI's Senior Director for Technology. Part of Sortwell's job involves bringing together AISI members to discuss common challenges, which can then become research projects.

> *"If I took the total carbon dioxide emissions from the world steel industry, and compared them to all other countries, steel would rank third. So you have China, the U.S., and what I call The Republic of Steel."*

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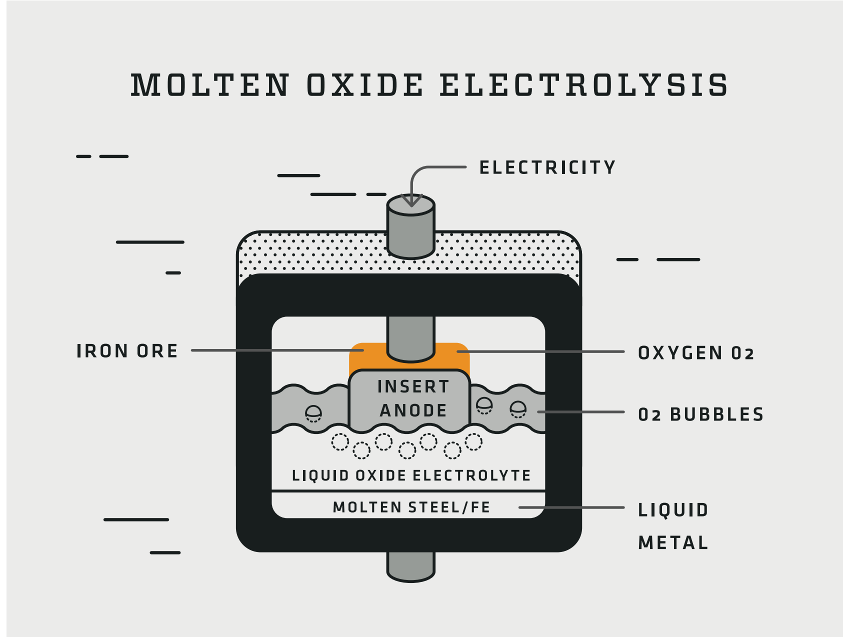
(1)https://www.worldsteel.org/
(2)https://www.ft.com/content/3bcbcb60-037f-11e9-99df-6183d3002ee1
(3)https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide
(4)https://www.worldsteel.org/about-steel/steel-facts.html
(5)https://www.gatesnotes.com/Energy/A-question-to-ask-about-every-climate-plan



One example is research toward completely new ways of producing steel.

Since 2005, AISI has directed work toward a novel process called flash ironmaking.[6] Because flash ironmaking "makes better use of our raw materials, it's expected to minimize carbon dioxide emissions and reduce energy requirements," says Sortwell. "It's a pretty big deal, with the potential to offset and eventually replace the blast furnace and other iron-making processes."

The project was a collaboration between the United States Department of Energy, AISI, Berry Metal Company, and the University of Utah. Last year the team finished tests of a lab-scale reactor, and "we now have a project plan to move forward with a pilot plant," Sortwell says.

Molten Metal

A little north of Boston, another company is developing a new approach to the production of steel. Based on work begun some 25 years ago by MIT's Sadoway, Boston Metal is zapping a molten mixture of iron ore and other materials with electricity to create steel and other metals.

Unlike the conventional technology for making steel, the Boston Metal process — called molten oxide electrolysis — does not use the element at the root of steel's carbon dioxide problems: carbon derived from coal. The principal byproduct of the new system? Oxygen, instead of CO_2.

"Our process uses electricity to go from a raw ore to a liquid metal," says Adam Rauwerdink, the company's vice president of business development. "The incumbent process starts with the same ore feedstock, but uses coal to form the reaction that frees the iron from the ore. So you get a lot of carbon dioxide."

The overall process is not new. Aluminum is produced this way. But making aluminum isn't as challenging. It takes place at significantly lower temperatures than those required for the electrolysis of iron ore, allowing reactors made of relatively low-cost materials that won't melt or otherwise disrupt the process through undesired reactions.

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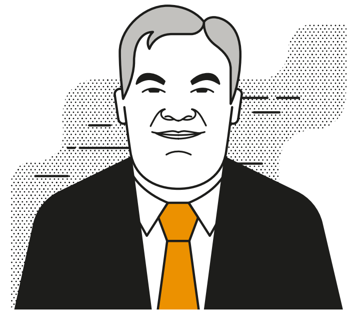
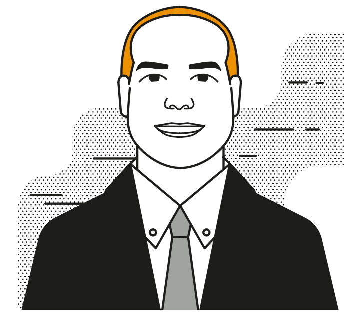
(6)https://www.energy.gov/eere/amo/downloads/novel-flash-ironmaking-process

Donald Sadoway
John F. Elliott Professor of Materials Chemistry, MIT & Co-Founder, Boston Metal



Mark Thimons
Vice President for Sustainability, American Iron and Steel Institute



Michael Sortwell
Senior Director of Technology, American Iron and Steel Institute

An ingot produced by Boston Metal.
Image courtesy of: Boston Metal

Pouring ingots at the Boston Metal production facility.
Images courtesy of: Boston Metal

The production of cement, the "glue" that binds together stone particles of different sizes to form concrete when mixed with water, is responsible for roughly eight percent of worldwide carbon-dioxide emissions.

Until about six years ago, there was no analogous set of materials for the production of steel via electrolysis. In particular, researchers could not find a suitable material for the anode of the reactor. Then Sadoway and colleagues solved the problem by identifying an inexpensive alloy of chromium and iron that could indeed withstand the extreme environment associated with molten temperatures hotter than lava (around 1,550°C, or ~ 3,000°F). "That was the breakthrough that really propelled Boston Metal," Sadoway says.

The company, which was founded in 2012, is growing quickly. Last fall there were nine employees; now there are 30. A series of larger and larger electrolysis cells, or reactors, have replaced the lab-scale cell developed by Sadoway, which was the size of a coffee mug. That cell operated at currents of only a few amperes. By next spring, Boston Metal aims to have a cell that will be roughly the size of a school bus and run at 25,000 amperes.

"Once we're confident we've got the design correct, we'll go to 50,000 amperes, and that's an industrial cell," says Sadoway, who expects to reach that goal by the end of 2021. Early aluminum industrial cells ran at about 50,000 amperes; today's aluminum factory runs at about 500,000.

Another way to reduce the environmental impact of steel and other metals is to create better versions that, for example, last longer, and so don't have to be replaced as often. Modumetal, a company based in Seattle, is doing just that with a new class of materials known as nano laminated alloys. Think "metallic plywood," says CEO Christina Lomasney.

Like Boston Metal, the Modumetal manufacturing process also uses electricity — rather than heat — to produce its products. In this case, however, a lower-temperature process (80-90°C) results in nanometer-thin layers of metal alloys that can be engineered to have a variety of important properties like better strength and resistance to corrosion. The company imparts those properties by modulating the electric field — hence the name Modumetal — as it passes through a proprietary mixture of materials where the reactions occur. "That's our secret sauce," Lomasney says.

The company's principal product is a coating called NanoGalv. "In a corrosive environment, it lasts 30 times longer than conventional galvanized steel," Lomasney says. Currently the company has two licensed manufacturers, Tri-Star Fasteners of Singapore, and Rollstud of the United Kingdom and the United Arab Emirates. "Other licensees representing other parts of the world are coming online soon," Lomasney says.

The Other Elephant

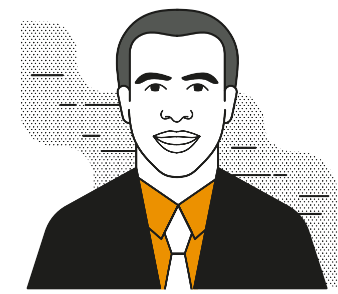
Tackling the carbon-dioxide emissions from the production of steel is key in the fight against global warming, but there's another elephant in the room that must also be addressed: cement. The production of cement, the "glue" that binds together stone particles of different sizes to form concrete when mixed with water, is responsible for roughly eight percent of worldwide carbon-dioxide emissions.[7]

Concrete, also like steel, is essential to society, and demand is growing. Behind water, it's the most widely used material on Earth. By 2050, we are expected to use four times the amount produced in 1990.[8]

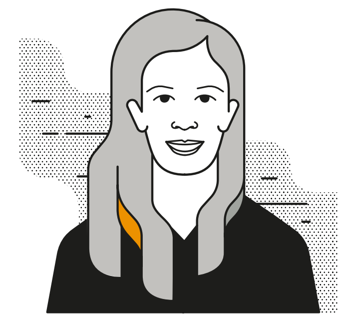
What can be done to cut the material's emissions? Professor Franz-Josef Ulm, faculty director of the MIT Concrete Sustainability Hub, holds up a small glass jar containing a black slurry that he believes represents the future of the industry.

That black slurry is the first cement with a completely new function: It can conduct electricity. Coupled to photovoltaic cells on the roofs of buildings or along highways, concrete made

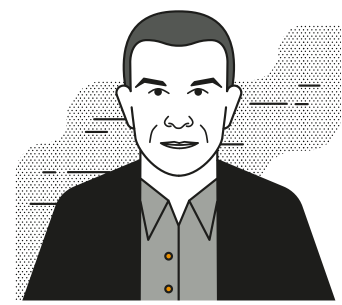
(7)https://edgar.jrc.ec.europa.eu/news_docs/jrc-2016-trends-in-global-co2-emissions-2016-report-103425.pdf
(8)https://www.chemistryworld.com/features/the-concrete-conundrum/3004823.article



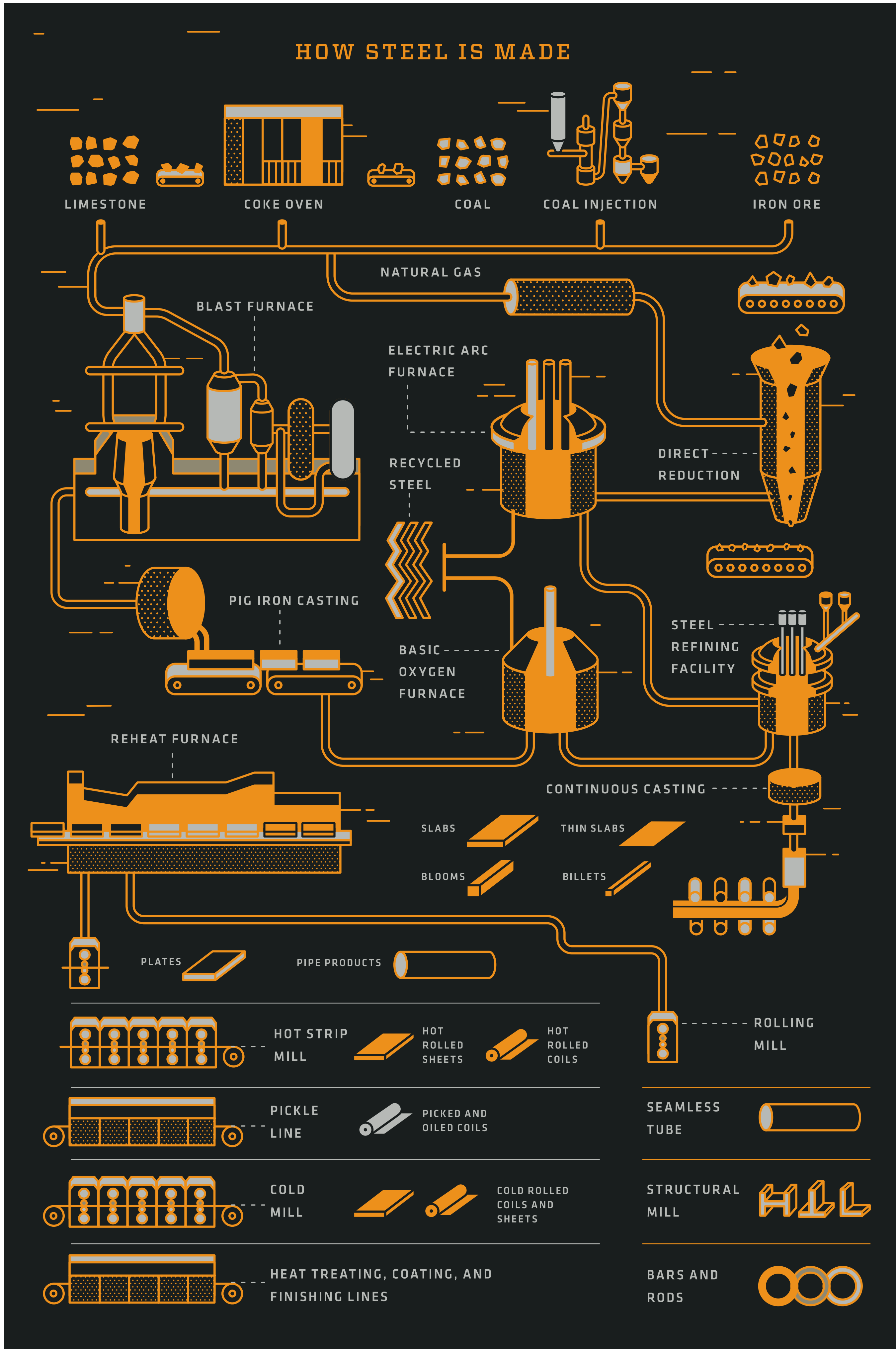
Adam Rauwerdink
VP of Business Development, Boston Metal

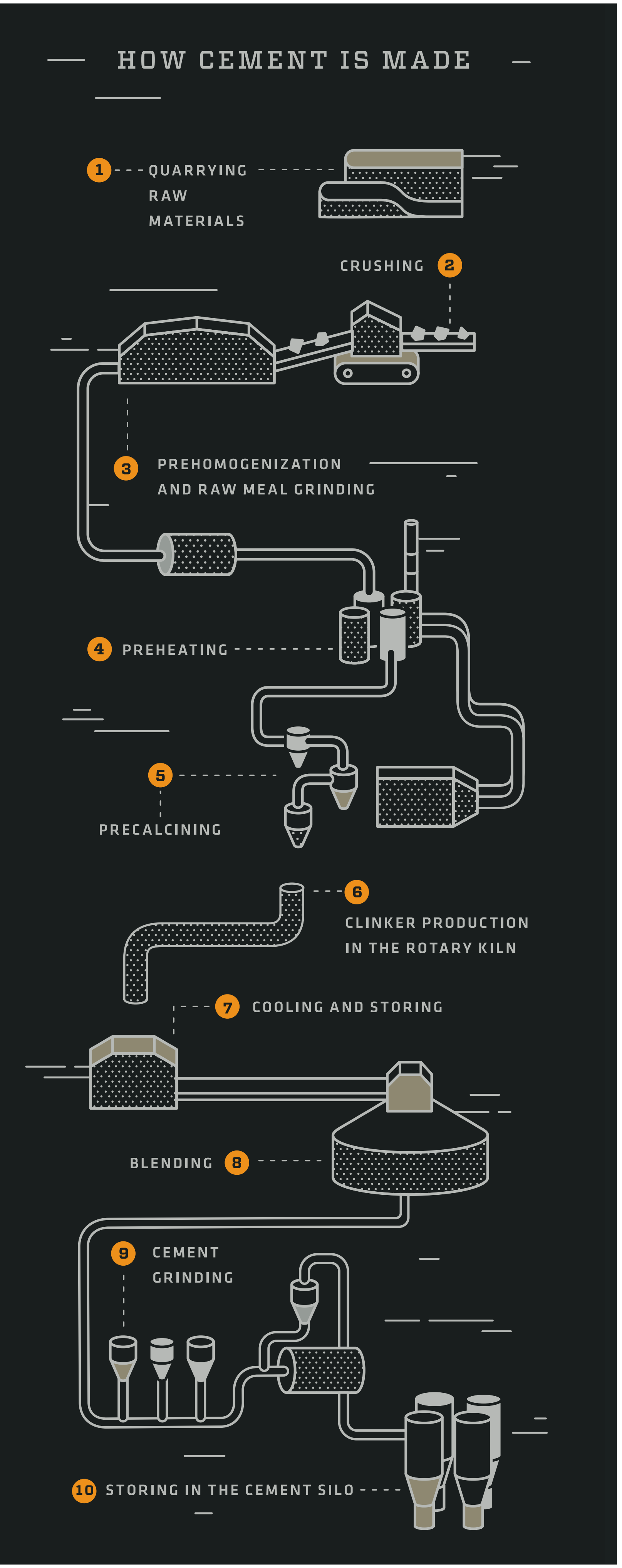


Christina Lomasney
Co-Founder, CEO & President, Modumetal



Professor Franz Josef Ulm
Professor & Faculty Director of Concrete Sustainability Hub, MIT





with the material could one day lead to self-heating roads (no salt necessary for ice removal) and floors that warm on demand, cutting the significant carbon-dioxide emissions associated with home heating from fossil fuels.[9]

"Right now, concrete is just there," Ulm says. But new, valuable functions in addition to strength — like the electrical conductivity being developed at MIT — could offset its overall environmental impact. "That puts concrete in another league, because now it becomes part of the solution," Ulm says.

Cutting concrete's carbon footprint by giving the material completely new functions is still in the lab. But Ulm notes three other approaches in use today for tackling the problem. The first involves optimizing the existing industrial process for the production of cement.

A second approach for cutting cement's emissions is to replace some of it with other materials. Several such supplementary cementitious materials already exist, including fly ash (a by-product of the coal industry) and silica fume (a byproduct from the production of silicon metal or ferrosilicon alloys).

It's also possible to create stronger cements by engineering the material's structure at the molecular scale. "Then we can do more with less material," Ulm says. This relatively new approach began around 2010 after Ulm and colleagues decoded the basic molecular structure of cement — essentially, its DNA.[10] That breakthrough is also behind Ulm's creation of the first cement with electrical conductivity. "Like many things in science, you come to [such discoveries] because you have understood something fundamentally new about a material," Ulm says.

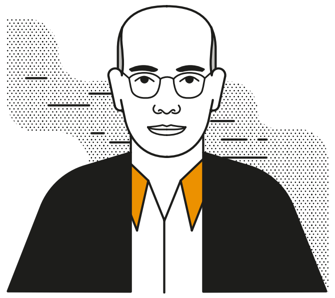
What about recycling? It's important, but not as straightforward as for steel, for a few reasons. Old concrete

(9)https://www.sciencedaily.com/releases/2019/08/190815113733.htm
(10)https://www.sciencedaily.com/releases/2009/09/090909141639.htm

that's crushed can replace some of the particles, or aggregate, that make up about 70-85 percent of the material, but it can't replace the key ingredient: cement. There have been studies toward recycling the cement, "but we have not yet succeeded," Ulm says.

Further, recycled aggregate can't be used in applications with strict quality standards because it could introduce impurities that affect the product. Bridges — which are meant to last for decades — are an example of such an application.

Finally, says Ulm, concrete is heavy. So even if you're recycling for aggregate, you must consider the life-cycle costs of transportation. Because of these challenges, says Ulm, "the recycling of concrete is still in its infancy, with high potential for transformational impact through science-enabled engineering."



Richard Riman
Distinguished Professor, Materials Science and Engineering, Rutgers University

Chris Stern
Co-Founder & CEO, Carbicrete

CO_2: Part of the Solution

Richard Riman remembers when he first came up with the idea that has since led to Solidia Technologies, a company in New Jersey that aims to lower concrete's carbon footprint by 70 percent.[11] "I was looking into my backyard in the early 2000s thinking about the carbon-dioxide problem when I thought, 'Why don't we just find ways to use CO_2 in concrete and other materials, for we would then consume CO_2 in very large quantities?'"

The Distinguished Professor at Rutgers University went on to found Solidia Technologies, applying that rationale — and his expertise in hydrothermal solidification technology — to cement. Working closely with co-inventor Vahit Atakan, who now serves as Solidia's chief scientist, the result is several Rutgers patents for a technique licensed by Solidia that uses carbon dioxide to cure, or harden, the concrete, instead of water.

Finding a way to consume carbon dioxide in and of itself cuts the gas's environmental footprint, but there is more. The technology also includes a cement manufacturing method that significantly reduces the amounts of CO_2 released during cement production.

That's because, for one, Solidia's cement can be made at significantly lower temperatures than conventional cement. This reduces the amount of fuel needed, whose combustion to generate heat releases less CO_2, Riman says. Further, the new cement requires less of cement's key ingredient — calcium carbonate — whose decomposition during cement production also releases CO_2. Taken together, along with its CO_2 curing process, that's why the company thinks it could have an outsized impact on carbon pollution.

To create concrete, Solidia mixes its cement with aggregate and a little water, then forms it into the desired shape. Add carbon dioxide, and the cement solidifies. "Under a controlled set of conditions, you can literally hear the material breathe in the CO_2," Riman says.

The new cement is composed of the same minerals already used in the industry — calcium carbonate and silica — they are just combined in a different ratio. And that means that the process can be quickly adopted by existing cement plants with no additional capital expenditures — a huge plus for cement manufacturers.

Among additional benefits, the "green" cement can be stockpiled for future use, resulting in "a huge improvement to the business model," Riman says. Conventional cement is not practical to store because it reacts and solidifies with water — even changes in humidity — resulting in unusable clumps. Solidia cement doesn't react with water, only CO_2. According to the company, the absence of a reaction with water can also save up to three trillion liters of fresh water each year.

In 2013, Solidia launched a pilot program with LafargeHolcim to supply EP Henry, a company that produces pavers, with Solidia cement. The product performance is excellent, as verified by third parties. In September of 2019, EP Henry became the first company in the world to sell pavers using Solidia cement.[12]

Other companies are also looking at solving the carbon dioxide problem by using the material in new products. Carbicrete, a firm out of Montreal, believes it has found a way to create concrete blocks that are carbon negative, or result in a net removal of the gas from the atmosphere. In 2018, the company was named one of ten finalists in the NRG COSIA Carbon XPRIZE, a competition focused on finding ways to use carbon dioxide in valuable products.[13] The winner, to be announced in fall 2020, will take home $20 million.

"The magic of Carbicrete is that we're solving three different problems," says CEO Chris Stern.

The company not only replaces cement — and its consequent emissions of carbon dioxide — but does so

> ***"Right now, concrete is just there," Ulm says. New, valuable functions in addition to strength — like the electrical conductivity being developed at MIT — could offset its overall environmental impact.***

Producing Soldia cinder blocks. [Bottom Right] Solidia concrete pavers.
Images courtesy of: Solidia Technologies

with steel slag, a waste material from the steel industry. The final coup? Carbicrete, which is based on research out of McGill University, creates its cement by reacting the steel slag with carbon dioxide.

"Carbon dioxide is generally not very reactive, but it's reactive with steel slag," Stern says. The end result: "We're permanently sequestering about a kilogram of CO_2 in each standard 18 kilogram concrete block we produce," which means the company's entire manufacturing process is carbon negative. Stern notes that a private consulting company has confirmed that conclusion.

The company is currently building a pilot plant to demonstrate the technology at scale. "We have to show that we can do this in the proper manner and at the cost model that we expect," says Stern.

In September 2019, a team led by Professor Yet-Ming Chiang of MIT reported "a new way of manufacturing [cement] that could eliminate [its greenhouse gas] emissions altogether, and could even make some other useful products in the process," according to MIT News.[14] Key to the work is an electrochemical process that uses electricity from renewable energy sources rather than fossil fuels to produce the cement. The new process also produces carbon dioxide, but in a pure, concentrated stream that could be captured and used for other applications like oil recovery. The CO_2 emitted by conventional cement plants is contaminated with a variety of materials that make recycling the gas impractical.

Carbon Upcycling Technologies (CUT), a five-year-old startup in Calgary, aims to make CO_2 green, according to its website. "We're using the pollution of today to create the materials of tomorrow," says CEO and Founder Apoorv Sinha.

CUT combines carbon dioxide

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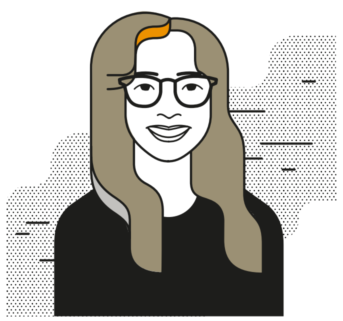
(11) https://www.solidiatech.com/impact.html
(12)h https://assets.ctfassets.net/jv4d7wct8mcO/1jzi-FYVVtEMqtIBCmVcySA/49e6d337d11687e2f8c82aa-6f9e7794a/EP_Henry_Solidia_Joint_Release_FINAL_9-12-19_.pdf
(13)https://asia.nikkei.com/Spotlight/Environment/Trapping-CO2-into-concrete-to-be-cheaper
(14)http://news.mit.edu/2019/carbon-dioxide-emissions-free-cement-0916

with cheaply available feedstocks to create a portfolio of nanoparticle additives that can make a variety of products stronger or more efficient. "We've been vetted for over 10 different industries, from concrete and plastic to solar panels and pharmaceuticals," says Madison Savilow, business development coordinator for the company.

In 2017, CUT became the youngest carbon utilization company to generate revenue with the sale of its first product, a coating for concrete that protects against corrosion.[15] Another one of its products reacts carbon dioxide with fly ash, a byproduct of burning coal, to replace 20 percent of the cement in concrete. That increases the compressive strength of the concrete by some 30 percent over concrete made with conventional fly ash products, says Savilow.

CUT has won or is a finalist in several competitions. For example, like Carbicrete, it is among the 10 finalists in the NRG COSIA Carbon XPRIZE. As part of that competition, the company is scaling up its production capacity. "Right now we can produce one ton of our powders a day," Savilow says. "Our next reactor for the XPRIZE will be capable of seven tons a day."

Today most of those separations happen in a process Dave likens to cooking pasta. But rather than boiling the pasta in water then pouring the mixture through a strainer, industries boil off all the water to get at the pasta at the bottom of the pot.



Madison Savilow
Business Development Coordinator,
Carbon Upcycling Technologies

Shreya Dave
Co-Founder & CEO,
Via Separations

At the Nanoscale

Shreya Dave points to thin sheets of material that range from a shimmery gold to a mottled brown and tan resembling bark. Those sheets represent a new filtration system that could significantly cut the energy use — and resulting greenhouse gas emissions — from the production of thousands of everyday products, from yogurt to plastic and fertilizers, not to mention many chemicals.

Dave, who is CEO of Via Separations, a startup in Somerville, Mass., notes that some 12 percent of all energy consumed in the U.S. is used to separate different compounds from one another in purification processes. "That's roughly equivalent to the gasoline in all the cars and trucks in the United States per year," she says.

Today most of those separations happen in a process Dave likens to cooking pasta. But rather than boiling the pasta in water then pouring the mixture through a strainer, industries boil off all the water to get at the pasta at the bottom of the pot. "We are working on creating a strainer at the molecular scale," she says, noting that the conversion to filtration could cut 90 percent of the energy consumed by those heat-based separation processes.

Filtration is not new. The water industry uses it for desalination. However, water filters don't work well for a variety of other applications like food processing or making paper, chemicals, and drugs. The Via Separations filter is based on a membrane developed by Dave and colleagues when Dave was a graduate student at MIT. "We take graphite — that's pencil lead — and explode it in a controlled chemical reaction that results in atomically thin flakes. Then we put them back together in the form of a thin flat sheet."

Those sheets are then stacked together, but minuscule spaces — pores — are stratified throughout, allowing passageways through the material. Each pore is only about one nanometer in diameter; contrast that to a human hair, which is about 75,000 nanometers wide. In a final step, the sheets are rolled up like carpet to be inserted into an existing filtration machine.

"So far, we've scaled up three orders of magnitude from the amount of material we made in the lab." The ultimate goal, says Dave, is to create sheets of material that are cheaper than what you'd pay for flooring at a hardware store. "The target for us is a few dollars a square foot. And we think we can achieve that."

Syzygy Plasmonics aims to dramatically reduce, and in many cases virtually eliminate, the carbon-dioxide emissions from chemical plants with a completely new type of reactor powered by light rather than the heat that comes from burning fossil fuels. "Our approach is a wild leap away from what is being done today," says Syzygy (siz-uh-jee) CEO Trevor Best.

That starts with size. Today's chemical plants are enormous structures with lots of smokestacks. In comparison, the photoreactor at the heart of the Syzygy plan is magnitudes smaller. As a result, Best expects that the company's first commercial photoreactor "will be about the size of a milk jug." Several would be linked together to produce chemicals in quantity, but the overall plant would still be pretty small. For that and other reasons, says Best, "we envision small-scale point-of-use manufacturing centers that can be put on site at a customer's location."

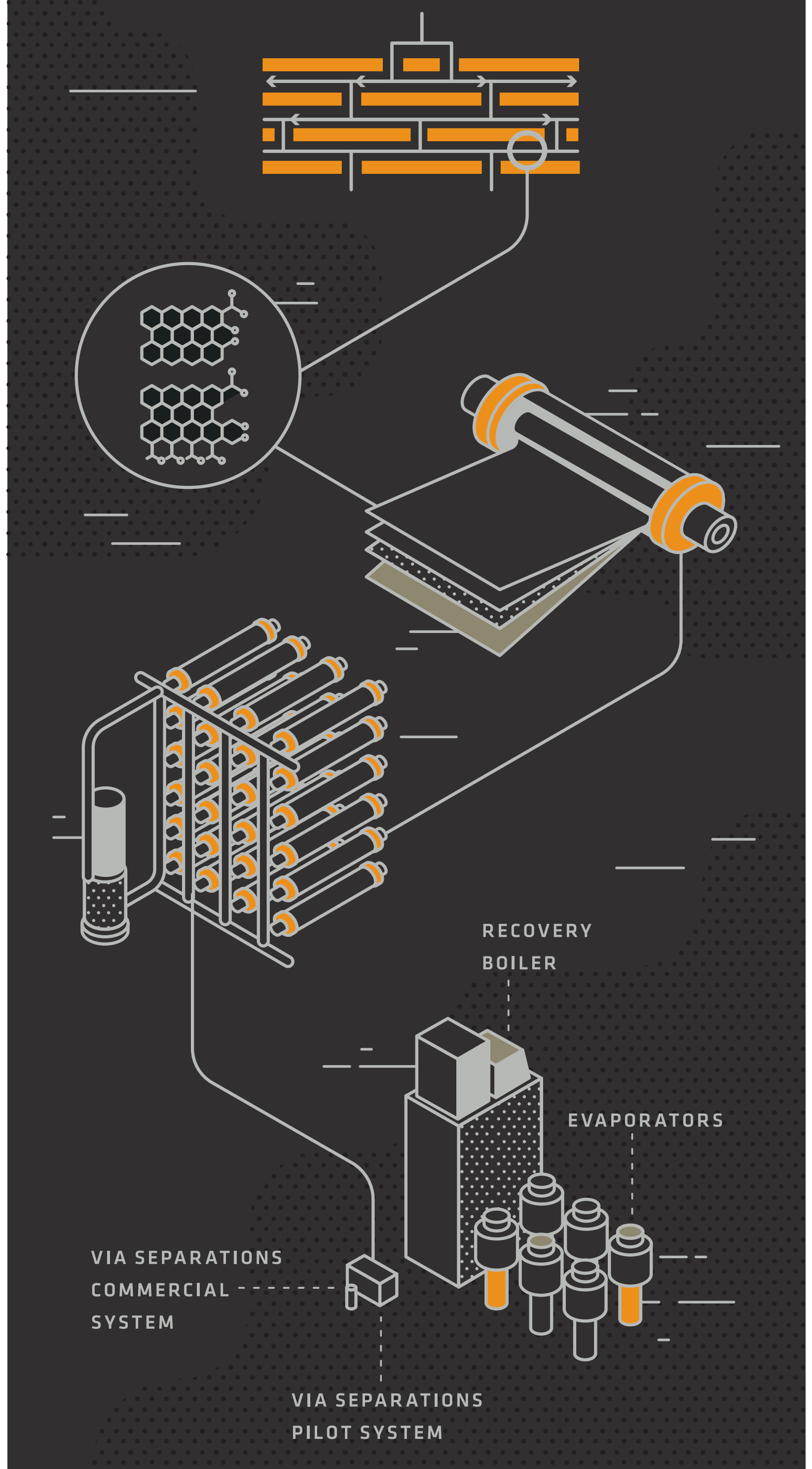
Other benefits: because the system is powered by LED lights, it operates at a temperature "very similar to your oven," Best says. In contrast, a common reaction today for producing hydrogen — one of Syzygy's target markets — runs at 1,500ºF. The system also does its work under much lower pressures. Taken together, that means the structure containing the reactor can be constructed using materials like aluminum, glass, or plastic, as compared to expensive alloys.

The breakthrough behind Syzygy is based on more than two decades of research at Rice University by Professors Naomi Hollis and Peter Nordlander. Both work in the field of nanophotonics, or the interaction of light with nanoscale structures. The two created what they call an antenna reactor, a hybrid structure that brings together two disparate materials. The first is a material that's "extremely good at harvesting light and turning it into a usable form of energy," Best says. That's the antenna. The second is a traditional catalyst, or material that is very good at performing chemical reactions.

Although Syzygy is only about two years old, the company has already shown that the technology works for more than a dozen different chemical reactions at the lab scale. More recently, the company has successfully scaled up a smaller number of these reactions into a bench-scale, single-cell photoreactor that "represents a world's first in this arena," Best said. Thanks to a successful funding round co-led by The Engine, the company aims to build a full-scale multi-cell photoreactor system in the early 2020s.

THE VIA SEPARATIONS PROCESSING SYSTEM

THE VIA SEPARATIONS MEMBRANE IS INTEGRATED INTO AN INDUSTRIAL FILTER. GROUPS OF THOSE INDUSTRIAL FILTERS ARE ASSEMBLED AND TRUCKED ON SITE. IN THIS CASE, THE PROCESSING SYSTEM IS USED AT A PAPER MILL.



Trevor Best
Co-Founder & CEO,
Syzygy Plasmonics

Challenges Remain

Radical innovations in the production of steel, concrete, and other materials are under development. Some are slowly moving into the marketplace. “But the market is a cruel arbiter,” says MIT’s Sadoway. “Nobody pays a premium for [something that’s] green. So you’ve got to make a product that’s as good as what’s being made by the incumbent today and is competitive in price.”

And according to a CNBC story about an analysis of corporate earnings profiles focused on steel, clean technologies for that industry won’t come online until the 2030s, and the resulting steel would be 20-30 percent more expensive.[16]

That said, while acknowledging the latter statistic, SSAB, the largest steel sheet manufacturer in Scandinavia, and collaborators are proceeding with their own approach toward fossil-free steel. A pre-feasibility study for the project, dubbed HYBRIT, expects that factors such as increasing costs for CO_2 emissions and lower costs for renewable energy will eventually make clean steel competitive with that produced through traditional processes.[17]

What about concrete? Says MIT’s Ulm of that industry, “they’re under enormous pressure to reduce their environmental footprint.” And in the United States, “it’s just a matter of time until legislation is passed that taxes carbon-dioxide emissions, which will give the industry an additional economic incentive to cut those emissions and push forward with transformational innovations.”

Nobody pays a premium for [something that’s] green. So you’ve got to make a product that’s as good as what’s being made by the incumbent today and is competitive in price.

Another challenge to getting innovative technologies into the marketplace is getting them included in industry spec sheets, or the accepted guidelines that set safety and performance standards. “The spec represents a barrier to entry for any technology,” says Modumetal’s Lomasney. “We’re selling into industries that have very mature procurement and supply chains and are not used to change or this level of innovation.”

Says Savilow of Carbon Upcycling Technologies, “talk to any materials company, and I guarantee that if they haven’t yet had their break into the spec sheets, that’s what they’re working towards.”

Finally, many of these technologies will only make sense with an abundant supply of renewable energy to run the reactions involved. “Otherwise you’re simply shifting the source of pollution,” Sadoway says.

Hope for the Future

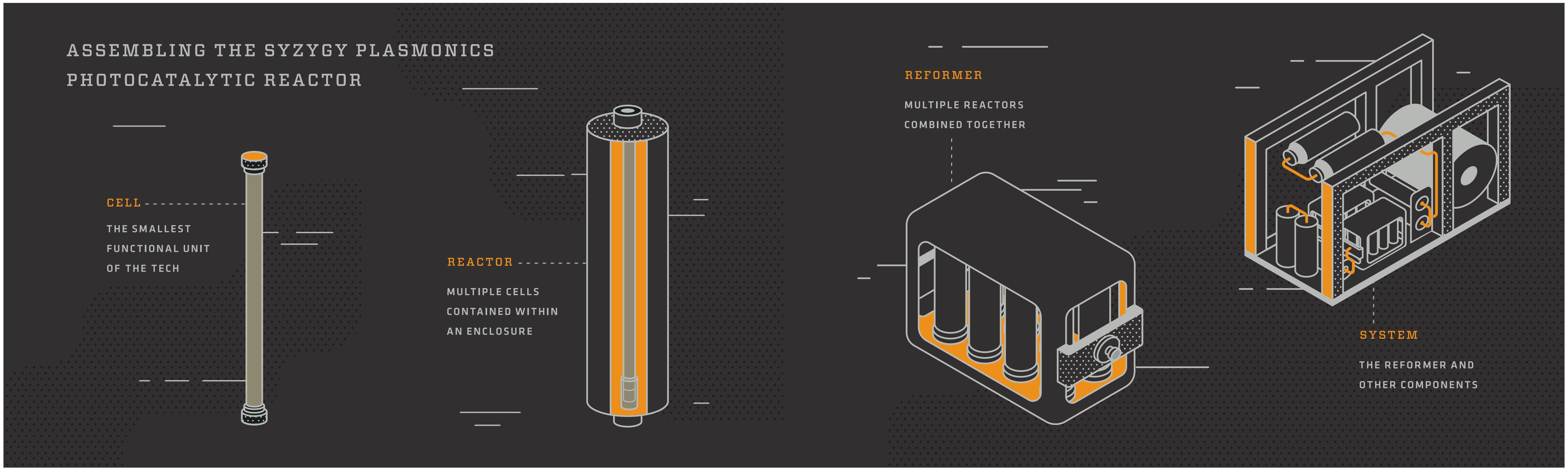
Climate change is in the news almost every day; witness the worldwide demonstrations that prefaced a United Nations summit in September 2019. “But you’re not seeing as much about climate solutions,” says CUT’s Savilow. Yet “there are many technologies and materials out there that are ready.” Carbicrete’s Stern would agree. “There are a lot of solutions; they just have to be implemented. We have to stop thinking about a magic bullet and just start doing something today.”

Bill Gates is also hopeful. In the conclusion to his blog about plans for dealing with climate change, he wrote:

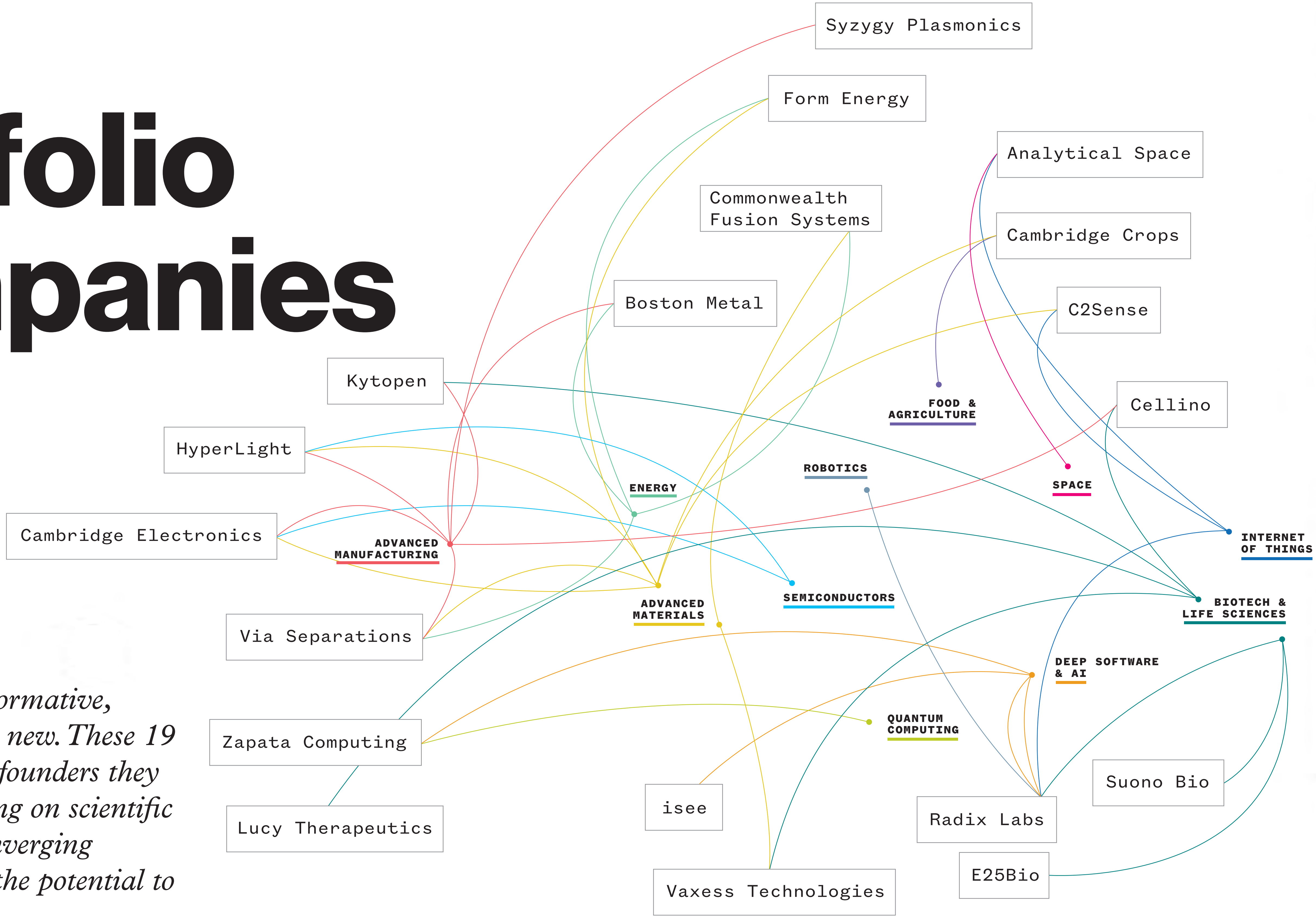
“I’m optimistic about all these areas of innovation — especially if we couple progress in these areas with smart public policies. Companies need the right incentives to phase out old polluting factories and adopt these new approaches. If all of these pieces come together, we will have a climate-friendly plan for steel, as well as cement, plastic, and the other materials that make modern life possible.”

Best, of Syzygy, notes that “the problems [related to climate change] that we have to overcome over the next few decades are enormous, and very intimidating. But I’m getting more hopeful for the future the more I work in this area. Not just because of our own technology, but because so many other people in other companies are joining in the fight with us.”+

(16)https://www.cnbc.com/2019/07/30/steel-sector-to-suffer-losses-rising-carbon-prices-climate-regulation.html
(17)https://www.ssab.com/company/sustainability/sustainable-operations/hybrit



The Portfolio Companies



We invest in the transformative, the audacious, and the new. These 19 companies — and the founders they represent — are working on scientific breakthroughs and converging technologies that hold the potential to redefine the future.

Syzygy Plasmonics

Founders	**|1|** Trevor Best, **|2|** Naomi Halas, **|3|** Peter Nordlander, **|4|** Suman Khatiwada
Background	Rice University, Baker Hughes
Industry	Advanced Manufacturing

Syzygy Plasmonics is pioneering a new type of chemical reactor driven by light rather than heat, enabling the potential for dramatically more efficient chemical manufacturing. At the heart of the reactor is a photocatalyst built with nanotechnology invented at Rice University. The company has focused its first efforts on hydrogen production, but its reactor platform has shown the ability to produce other industrial gases and chemicals without the high carbon emissions and costs associated with typical production processes. Hydrogen may be the lightest element in the universe, but isolating and transporting it exacts a massive environmental toll. Syzygy's reactor is simple, small, and efficient enough to reduce net global carbon production emissions of the gas at scale. It also has the potential to eliminate hydrogen's cumbersome transportation chain. Instead of producing the gas at a central location, liquefying it, trucking the liquid, and re-gasifying the liquid, a Syzygy reactor the size of an outbuilding could be installed on site to produce only the amount of gas that is required, exactly when it is needed.

This decentralization will drive down hydrogen costs to levels competitive with gasoline and diesel, accelerating the adoption of hydrogen fuel cells in industrial and heavy-duty vehicle applications like forklifts, buses, and trucks. It will also help decrease the costs and emissions associated with producing the 61 million metric tons of hydrogen consumed by chemical production and refining. If Syzygy's reactor were solely designed to produce hydrogen, it would fundamentally redefine an industry. But the plasmonic nanoparticle platform at the heart of the reactor is capable of much more.

Syzygy's core photocatalysis technology represents the culmination of over two decades of research by professors and scientific co-founders Dr. Naomi Halas and Dr. Peter Nordlander at Rice University. The professors, working out of the University's Laboratory for Nanophotonics, invented the technology while investigating the interactions of light and matter at the nanoscale.

Trevor Best and Dr. Suman Khatiwada, Syzygy's co-founders, saw the business potential for the professors' laboratory breakthrough and set it on a path to commercialization. Best and Khatiwada met in the Houston-based research laboratories of the industrial oil field services company Baker Hughes, Best as a manager in process improvement and Khatiwada as a research scientist. The two shared an entrepreneurial spirit and connected over their drive to create positive impact.

The company, whose name refers to the alignment of three planetary bodies, was launched in 2018 with the intention of aligning energy, technology, and sustainability in a single world-changing business. The team has since scaled the productivity of its reactor technology more than 10,000x and improved energy efficiency more than 100x.

Best is quick to note that the early success of Syzygy is anything but fortuitous. He attributes such rapid improvements in its core reactor technology to a team that is simultaneously the most qualified in the world at what they do and committed to a future in which chemicals are created, and pollutants remediated, with a technology powered by light.

Developing a chemical reactor driven by light instead of heat enabling cheaper, modular, scalable on-site production of chemicals.

A new approach to curing neurological diseases using mitochondrial-based therapies.

Lucy Therapeutics

Founder	Amy Ripka
Background	University of Wisconsin-Madison, The Scripps Research Institute
Industry	Biotech & Life Sciences

Imagine a world in which doctors can diagnose and treat patients before the tremors, the dementia, or the seizures from neurological diseases like Rett Syndrome, Alzheimer's, and Parkinson's take control. This is a world that Lucy Therapeutics is working to realize.

For Amy Ripka, the company's founder, any significant progress in developing treatments for neurological diseases will require non traditional methods. The siloed manner through which disease targets are normally identified is potentially why such treatments remain elusive, even after decades of research. And it's why Ripka is taking another approach — she is selecting drug targets based on a deep understanding of the crossover chemical and biological interplay at work in these diseases.

This strategy led Ripka to a therapeutic target that mirrors the complexities of the diseases themselves: the mitochondria. She has linked neurodegenerative disease to dysfunctional mitochondria in neurons and is pioneering a new class of treatments designed to address such dysfunction.

The insights underlying Lucy Therapeutics' drug discovery platform give it a substantial advantage, especially when one considers the neuroscience industry's limited success identifying targets. These insights also unlock the door to a biomarker that would enable early, pre-symptomatic diagnosis.

Ripka's approach requires her to read exhaustively beyond her field and to understand how to apply her disparate insights in an integrated fashion. Finding such a cross-functional scientist is not common; finding one who is pioneering potential curative treatments is downright rare.

Ripka has deep experience in the complementary realms of big pharma, biotech, and contract research organizations. After receiving a PhD in chemistry from the University of Wisconsin-Madison, she went on to work in the lab of Nobel Laureate K. Barry Sharpless at The Scripps Research Institute, followed by a career that included time at Bristol-Myers Squibb, EnVivo Pharmaceuticals, and WuXi AppTec, among others.

This variety of professional roles taught Ripka to approach the traditional drug discovery process in an untraditional way. She saw the inefficiencies in today's discovery pathways first hand — the work spent pursuing a solution without the realization that a scientist in a similar, but seemingly unrelated, field had already trod that ground and gained valuable data. Ripka notes that these pathways lack "cross-fertilization," or the interdisciplinary flow of knowledge in pursuit of a singular goal.

Similar to the web of neurons that they impair, neurological diseases like Parkinson's, Alzheimer's, and Rett Syndrome are complex and mysterious things. Ripka's insights into the root of these illnesses will guide the team at Lucy Therapeutics to lay bare such mysteries and reveal treatments that will fundamentally change our relationships with some of our most devastating and unpredictable diseases.

Launching a satellite network to connect existing satellites to Earth 24/7.

Analytical Space

Founder
Dan Nevius

Background
NASA, Planetary Resources, White House, HBS

Industry
Space, Internet of Things

Analytical Space is building a network of in-orbit communication relay satellites that offer expanded connectivity for data transfer, without any change to existing hardware. This results in faster data downloading, more access to download windows, lower latency, and improved cost structures, while being compatible with heritage satellites and new satellites alike.

Analytical Space will liberate and deliver terabytes of untapped data gathered by hundreds of satellites, giving humanity a more informed and dynamic picture of everything from industrial agriculture to weather.

Boston Metal

Founders & Leadership
Tadeu Carneiro, Rich Bradshaw, Adam Rauwerdink, Donald Sadoway, Antoine Allanore, Bob Hyers, Jim Yurko

Background
MIT Department of Materials Science and Engineering

Industry
Advanced Manufacturing, Energy

Boston Metal has invented a coal-free, emissions free, modular method of industrial steel and ferroalloy production using electricity. It's called molten oxide electrolysis (MOE) and combines transformative materials engineering and novel systems engineering with elements from industrial aluminum production, traditional blast furnaces, and arc furnaces to produce steel more efficiently, at lower costs than traditional methods, and with zero greenhouse gas emissions.

Today, the steel industry is the largest industrial source of CO_2 emissions because of a reliance on coal. Boston Metal removes coal from the process, driving CO_2 emissions to zero, while also providing substantial OpEx and CapEx savings.

A new process to produce steel more efficiently, at a lower cost, and with zero greenhouse gas emissions.

Developing gas sensing technologies that transform the gases around us into useful, quantifiable knowledge.

C2Sense

Founders & Leadership
George Linscott, Timothy Swager, Eric Keller, Jan Schnorr

Background
MIT Department of Chemistry

Industry
Advanced Materials, Internet of Things

A digital olfactory sensor platform for industry, C2Sense's technology transforms smell into real-time data that can be accessed remotely. With high-fidelity electrochemical sensors at a low price point, C2Sense will empower a broad array of industries including those involved in food supply, product authentication, and chemical production to take control of their environments.

By making gases detectable and trackable on an industrial scale, C2Sense reduces food waste, improves safety and health of employees, and builds a more efficient and productive world.

Cambridge Crops

Founders
Adam Behrens, Sezin Yigit, Benedetto Marelli, Livio Valenti, Fiorenzo Omenetto

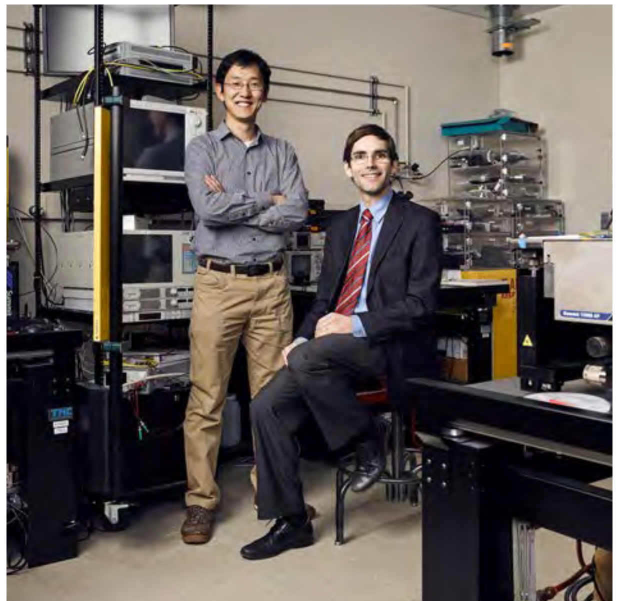
Background
MIT Laboratory for Advanced Biopolymers, Tufts University SilkLab

Industry
Food & Agriculture, Advanced Materials

Cambridge Crops is addressing the problem of food spoilage and waste by pioneering a natural, ultra-thin water-based coating that preserves the freshness of food longer. It's tasteless and invisible and can be applied to everything from fresh and cut produce to proteins like meat and fish. The coating dramatically extends shelf life by slowing the exchange of gases that cause decay, making food accessible to more people for longer times. In addition, the coating has the potential to support enhanced nutrients for food and also help reduce packaging.

One third of the food produced in the world is wasted. Cambridge Crops' technology helps to reduce food spoilage across the supply chain, decreases logistics costs, and makes healthy food more accessible.

A natural, sustainable and edible protective food coating that significantly increases shelf life and reduces food waste.



Transforming power electronics with a new generation of GaN-powered chips.

Cambridge Electronics

Founders
Bin Lu, Tomás Palacios

Background
MIT Microsystems Technology Laboratories, MIT Department of Electrical Engineering and Computer Science

Industry
Semiconductors, Advanced Materials

Today's electronics rely on silicon processing — from data centers to industry, electric vehicles to consumer electronics — the ubiquitous material is used to control and convert power. As these technologies advance, industries are challenged to build increasingly efficient (and increasingly small) power electronics. In many cases we have reached the limits of silicon. Cambridge Electronics has invented a proprietary gallium nitride (GaN) technology that is less expensive and exponentially more efficient than silicon, while also having a smaller footprint.

Cambridge Electronics' technology will bring significant energy savings to diverse and power-reliant industries like data centers, renewable energy, manufacturing, automotive, and consumer electronics.

Cellino

Founders
Nabiha Saklayen, Matthias Wagner, Marinna Madrid

Background
Harvard Physics Department, Harvard School of Engineering and Applied Sciences (SEAS), Harvard Medical School

Industry
Biotech & Life Sciences, Advanced Manufacturing

Cellino has built the first platform that enables precise control over iPS cell fate in their natural environment. The Cellino Tissue Engineering Platform manufactures high-quality, impurity-free tissues for new regenerative medicines. Cellino will use its platform to manufacture tissues at scale, delivering the highest quality human tissues made to date. Such tissues are poised to lead to significant gains in therapeutic benefit to the patient.

Cellino's approach for high-throughput digitization of engineering human cells will create new tissues with significant gains in therapeutic benefit to the patient and further transform the biotech industry.

Pioneering the next pillar of the regenerative medicine industry through precision cell production.

Developing safe, unlimited, carbon-free fusion power to generate baseload electricity in 10-15 years.

Commonwealth Fusion Systems

Founders & Leadership
Bob Mumgaard, Brandon Sorbom, Dan Brunner, Dennis Whyte, Martin Greenwald, Zach Hartwig

Background
MIT Plasma Science and Fusion Center

Industry
Energy, Advanced Materials

Commonwealth Fusion Systems (CFS) aims to provide a new path to fusion power by combining proven fusion physics with revolutionary magnet technology to deploy the first working, economic fusion reactors to the world. The team will develop high-field magnets based on a new class of high-temperature superconductor materials that allow fusion reactors to be 10 times smaller, economically feasible, and operational in the next 10 years.

Fusion energy is the holy grail of clean energy: limitless, no greenhouse gases, baseload, concentrated, no meltdown, and no proliferation. If successful, the world's energy systems will be transformed.

E25Bio

Founders
Irene Bosch, Lee Gehrke, Bobby Brooke Herrera, Jeff Takle

Background
MIT Institute for Medical Engineering & Science,
MIT Tata Center

Industry
Biotech & Life Sciences

E25Bio is pioneering an at-home rapid fever panel for mosquito-borne diseases. With its first-in-class antibodies identified with a novel screening method, E25Bio's diagnostic test is the first of its kind to distinguish between dengue (as well as all four subtypes of the disease), chikungunya, and Zika. The test, which works with whole blood from a simple finger prick, is the first of its kind to screen for active virus, making it more effective than a traditional blood draw.

E25Bio is putting a specialized central medical testing facility within a single over-the-counter test. Initially, the company's rapid fever panel will empower patients, healthcare workers, and public health officials in Latin America. But the company's ability to quickly produce effective antibody pairs means that it has the potential to help patients across the globe.

Enabling rapid, accurate diagnosis of infectious disease at the point of care.

Engineering a bidirectional power plant to make renewable energy available 24/7.

Form Energy

Founders
Mateo Jaramillo, Yet-Ming Chiang, Ted Wiley,
William Woodford, Marco Ferrara

Background
MIT Department of Material Science and Engineering, 24M Technologies, A123, Tesla Energy

Industry
Energy, Advanced Materials

Form Energy will solve large-scale renewable energy's most fundamental limitation — reliability — through energy storage. Rather than thinking of batteries in the traditional sense, simply as storage vessels, Form Energy is designing 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 grid.

Form Energy will help bring renewables to the masses by storing enough energy from sources like wind and solar to power thousands of homes and businesses.

HyperLight

Founders
Mian Zhang, Marko Loncar, Cheng Wang

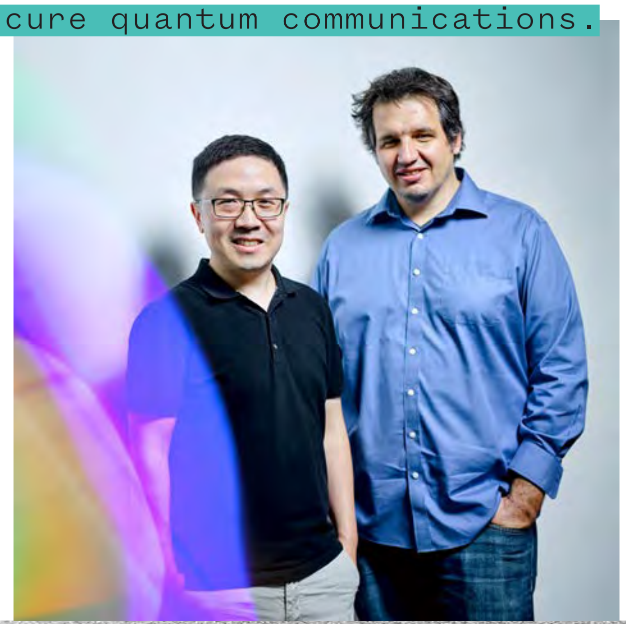
Background
Laboratory for Nanoscale Optics at Harvard University

Industry
Semiconductors, Advanced Materials, Advanced Manufacturing

HyperLight has invented unique processes and designs for fabricating integrated, chip-scale Lithium Niobate (LN) modulators with extremely low signal loss. These integrated optical circuits hold the potential to reshape the world's relationship with optical data and enable novel functionalities from communication to spectroscopy. The startup's technology was developed at Harvard University and is featured in multiple publications in the journal *Nature*.

The information age relies on billions of devices converting signals between electricity and light waves. These integrated light circuits are the backbone of telecommunication, data centers, and even secure quantum communications. HyperLight's devices will force industries to rethink and reimagine their current standards.

Producing ultra-efficient chip-scale optical circuits to de-bottleneck data centers, telecommunication networks, and secure quantum communications.



Engineering an AI-powered autonomous driving system to automate the logistics industry from shipping yards to highway freight transportation.

isee

Founder
Yibiao Zhao, Debbie Yu, Chris Baker

Background
MIT Computational & Cognitive Science Group

Industry
Deep Software & AI

isee is engineering next-generation, humanistic AI to automate the logistics industry from dock to door. Their technology is built for complex environments with high uncertainty (shipping yards and congested highways), and can integrate into an existing logistics workflow without infrastructure change. In the world of autonomous transportation, the startup was the first to achieve exit-to-exit autonomous highway driving, the first to merge onto a highway in heavy snow, and the first to handle congested traffic better than a leading autonomous driving startup.

isee plans to first automate the shipping yard, reducing yard costs by 50 percent and increasing yard throughput by 30 percent. The same AI that will power yard trucks can be used to transport freight across our highways — it will add value and increase safety throughout the logistics supply chain.

Pioneering superior cellular engineering, from discovery to the clinic.

Kytopen

Founders
Paulo Garcia, Cullen Buie

Background
MIT Department of Mechanical Engineering

Industry
Biotech & Life Sciences, Advanced Manufacturing

Kytopen aims to transform the cell and gene therapy industry by dramatically improving the efficiency of the genetic engineering of cells. The company's microfluidics and electric field-based platform can accelerate and automate the genetic engineering of cells 10,000 times faster than current methods. With continuous flow of cells during genetic manipulation, the products in development address both small and large sample volumes, and enable drug discovery to manufacture therapies.

Cell and gene therapies have the potential to truly cure diseases and fundamentally change the way medicine is practiced. However, they currently suffer from major challenges in efficiency, reproducibility, and cost. Kytopen's solution can solve a huge bottleneck in the development processes, and will reduce the cost and accelerate time to market for discovery and manufacturing of these therapies.

Radix Labs

Founder
Dhasharath Shrivathsa

Background
Olin College, MIT Media Lab

Industry
Robotics, Deep Software & AI, Internet of Things, Biotech & Life Sciences

Radix Labs has built a programming language that unites biologists and their lab machinery in one automated unit. This programming language is the heart of software that manages both human and machine tasks. It is the first time disparate lab machinery can communicate with one another under the control of one centralized platform — it is, for all intents and purposes, an operating system for biology labs.

Designed around an approachable user interface, this software solution intentionally distances the specification of the program — in this case, the lab protocol — from the execution. It does this with the hope that biologists spend less time in the lab, and more time focusing on experimental design and analysis.

Automating lab equipment and processes to reclaim the $28B lost in unreproducible research.

Delivering medicine with ultrasound to treat traditionally "undruggable" diseases.

Suono Bio

Founders & Leadership
Carl Schoellhammer, Robert Langer, Amy Schulman, Gio Traverso, Lisa Ricciardi

Background
MIT Department of Chemical Engineering

Industry
Biotech & Life Sciences

Suono Bio has reimagined ultrasound as an effective and elegant delivery mechanism for the most delicate therapeutics. Its technology can push molecules like DNA, RNA, and proteins directly into cells without disrupting the surrounding tissue or harming the molecule itself. The flexibility and efficacy of the Suono Bio therapeutic platform brings with it the potential to treat and cure diseases with targets once deemed undruggable.

Suono Bio will more effectively treat challenging chronic gastrointestinal diseases and enable new therapies for other pressing health challenges like diabetes, cancer, and viral infections.

Vaxess Technologies

Founders
Michael Schrader, Kathryn Kosuda, Livio Valenti, Patrick Ho, David Kaplan, Fiorenzo Omenetto

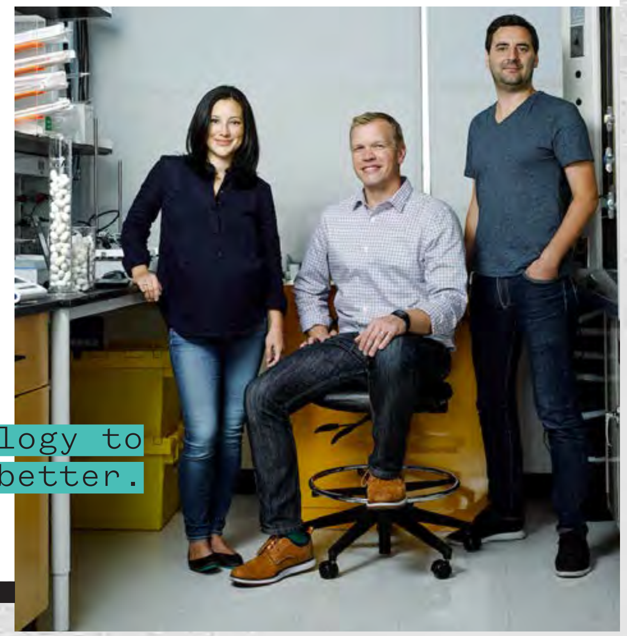
Background
Harvard Business School, Tufts University SilkLab

Industry
Biotech & Life Sciences, Advanced Materials

Vaxess Technologies is pioneering a technique it calls Infection Mimicry to help increase the effectiveness of immunotherapies for infectious diseases and cancer. The company's first product, named MIMIX, is inspired by the body's natural immune response to infection. MIMIX is a smart-release therapeutic patch that, after only minutes of wear-time, can release treatments into the skin at precise rates for up to months after the initial application.

The same biology that allows MIMIX to activate the immune system against infectious diseases like influenza can also be used to activate the immune system against cancer cells. When a MIMIX patch loaded with a chemo agent is applied to a certain tumors, for example, it kickstarts a natural immune response, eventually eliminating metastases throughout the body.

Harnessing evolutionary biology to make immunotherapy work better.



Building ultra-efficient molecular filters for industrial processes with the potential to save 90 percent of the energy used in chemical separation.

Via Separations

Founders
Shreya Dave, Brent Keller, Jeff Grossman

Background
MIT Department of Materials Science and Engineering

Industry
Energy, Advanced Materials, Advanced Manufacturing

Separation processes are the building blocks for materials, chemicals, and consumer goods — they are core to the industrial ecosystem. Currently, most separations are done with thermal processes such as evaporation and distillation, which are very energy intensive. Via Separations is commercializing novel membrane materials and manufacturing processes to replace evaporation and distillation with filtration.

The company's technology has the potential to replace thermal separation processes, saving the energy equivalent used by the entire gasoline industry every year in the U.S.

Zapata Computing

Founders
Christopher Savoie, Alán Aspuru-Guzik, Jonathan Olson, Peter Johnson, Yudong Cao, Jhonathan Romero Fontalvo

Background
Harvard Department of Chemistry, University of Toronto Department of Chemistry

Industry
Quantum Computing

The team at Zapata Computing writes algorithms that harness the power of quantum computing to help predict and simulate some of the universe's most complex interactions, such as the behavior of molecules at an atomic level. When used in tandem with quantum hardware, these algorithms have practical industrial applications, like the optimization of supply chains and travel routes, or the prediction of drug efficacy before compounds are synthesized in the lab.

By creating algorithms that bridge advances in quantum computing hardware and commercial applications, Zapata has the potential to discover new life saving molecules, energy-efficient materials, and much more.

Creating software for quantum computers to solve some of the most difficult computational problems known.

The Engine is Expanding

An exterior view of The Engine's new home.

In fall 2019, construction started on The Engine's 200,000 sq/ft expansion project in Cambridge, Mass. The Engine, in collaboration with MIT, is renovating a former Polaroid building at 750 Main Street to serve as a hub for Tough-Tech growth.

This new hub will provide a place for companies to put their ideas into action — helping them build transformative technologies as efficiently, economically, and effectively as possible. It will have a natural proximity to academic institutions; access to talent, flexible and affordable lab and fabrication facilities, and a network that will foster relationships for market readiness. It aims to connect the diverse Tough Tech ecosystem — entrepreneurs, scientists, engineers, leaders in academia and business, investors, and policymakers.

The space is designed for companies at the convergence of technology disciplines across engineering and physical sciences, where access to diverse space and tools are essential for success. It will hold shared fabrication space, chemistry and biology labs, office space, and other flexible space for 100 companies and approximately 1,000 entrepreneurs.

"We have the chance to forge a foundational infrastructure that can potentially change the geography of innovation. A thriving hub can propel the Boston region into the future as a magnet for world-changing Tough Tech companies." Katie Rae, CEO & Managing Partner

Tough Tech is ...

> Engineering an AI-powered autonomous driving system to automate the logistics industry from shipping yards to highway freight transportation.

> Pioneering superior cellular engineering, from discovery to the clinic.

> A new approach to curing neurological diseases using mitochondrial-based therapies.

> Automating lab equipment and processes to reclaim the $28B lost in unreproducible research.

> Delivering medicine with ultrasound to treat traditionally "undruggable" diseases.

> Developing a chemical reactor driven by light instead of heat enabling cheaper, modular, scalable on-site production of chemicals.

> Engineering a simple patch that enables sustained release of medicines and vaccines through the skin.

> Building ultra-efficient molecular filters for industrial processes with the potential to save 90 percent of the energy used in chemical separation.

> Creating software for quantum computers to solve some of the most difficult computational problems known.

THE ENGINE
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