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The Food Issue

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ALL IN ON BEATS

Lab-grown meat, artificial human breast milk, genetically modified pigs, a cauliflower field farmed by robots—if that's the kind of science-fiction-y stuff you expect to read about in a special issue on technology and food, you won't be disappointed—see pages 26, 32, 44, and 50. (And if you like actual science fiction, turn to page 80.)

What makes these technologies so fascinating? Sure, it's claimed that they'll make food production better—more humane, more reliable, more efficient. But beyond that, I think we're at once intrigued and repulsed by the idea that something as familiar, essential, and "natural" as food can be deconstructed and rebuilt from its component cells, tweaked like a piece of software, or grown without ever being touched by a human hand.

This reflects an evolution in Western food culture. If mid-20th-century advertisements extolled synthetic foods in garish colors, and television shows told us we'd soon have all our nutritional needs met by three pills a day, today we fantasize about ancient grains and heirloom tomatoes in limitless abundance. But that also means we prefer not to acknowledge the truth: there's already precious little that's "natural" about how we get most of our food.

Today's food system bears little resemblance to the one of just a couple of generations ago. It is far more industrial and globalized, and in much of the world it yields many times more crops per acre of land, thanks to new fertilizers, pesticides, and seed varieties. The most mundane processes, from walnut picking to potato breeding, are technologically mediated from top to bottom (page 15) and are only becoming more so. We can make a piece of food take on any color in the spectrum, where once we were restricted to naturally occurring pigments (page 38). Industrial-scale fermentation, long-distance transportation, packaging, and refrigeration completely changed what foods are available when and where; newer advances like e-commerce, CRISPR, and precision agriculture are expected to have similarly far-reaching effects in the coming years (page 24). In our kitchens, yesterday's gadgets for gourmets are becoming today's essential appliances, raising the bar for home cooking ever higher (page 72).

And yet, for all its abundance and reach, the food system fails to feed hundreds of millions of people each year—and this figure, shockingly, is rising (page 74). Why?

Gideon Lichfield is editor in chief of MIT Technology Review.

The obvious answer is that the food system is not actually designed to feed people. It's designed to turn a profit, and typically it achieves that by maximizing yields and efficiencies. This might lead to the production of a lot of food, but often in the wrong places, at the wrong times.

So what would happen if we made adequate nourishment a basic human right and rewrote the usual rules of capitalism to achieve it (page 10)? What if, instead of making maximal productivity the ultimate goal and using technology to boost it, we aimed for universal balanced nutrition and sustainable agriculture, and sought out both new technological solutions and traditional farming practices as a way to get there (page 66)? We've already added minerals and vitamins to various foods to combat nutrient deficiencies that sicken billions of people every year; what if we kept on going (page 58)?

The message in all this is one that MIT Technology Review delivers time after time: technology can yield great benefits to humanity, but only if we choose to deploy it in pursuit of those benefits. It may be a tired old nostrum, but it's never more self-evidently true than with food—a technological product that every human being relies on almost every single day.

IAN ALLEN


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THE FOOD ISSUE

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Technology has completely transformed the global food supply system, yet still hasn't brought an end to hunger. For that to happen, the choices we need to make are political, not technological.

By
FABIO PARASECOLI

Super-market forces

We won't easily forget how we worried about food in the first days of the pandemic: empty shelves, scarce products, and widespread hoarding became an alarming reality around the world. While being reassured that the disruptions were "temporary," Americans also heard troubling news about farmers plowing crops back into their fields, dairy farmers pouring milk into the sewers, meatpacking plants shutting down. Meanwhile, lines at soup kitchens and food banks grew.

As it turns out, these failures derived from built-in features of our food system. It was cheaper to destroy crops than harvest and process them when bulk buyers like schools and catering businesses all but suspended purchases. Dairies set up for selling big volume weren't equipped to shift their packaging machines to consumer-sized containers. Meatpacking plants revved up to meet demand—a situation that required as many workers as possible to crowd in along processing lines. Predictably, many fell ill, and plants across the country were forced to shutter.

The shock of the virus's first wave exposed the inner workings of our interconnected system of food creation and delivery—and its weak spots—to many of us who'd never given it a second thought. That system is, of course, a result of decades' worth of technological advances, from globe-spanning shipping and refrigeration networks to commodity markets (running on high-speed internet and massive cloud-computing infrastructure) that provide the capital to make it all run. There may yet be more unpleasant surprises in store for millions of people around the world as the pandemic plays out. But this moment offers us an opportunity to examine how we got to this point, and how to change things for the better.

The cost of growth

Simply put, the modern food system is a product of the forces inherent in free-market capitalism. Decisions on where to invest in technological research and where to apply its fruits have been guided by the drive for ever greater efficiency, productivity, and profit.

The result has been a long, steady trend toward greater abundance. Take wheat production as an example: thanks to the railways, the introduction of better equipment, and the adoption of higher-yield varieties, output in the US tripled between the 1870s and the 1920s. Similarly, rice production in Indonesia tripled in 30 years after the mechanized, high-input methods of the Green Revolution were adopted in the early 1970s.

PABLO DELCAN

This is what happens when a system fine-tuned for efficiency, productivity, and profit collides with a shock.

But as we all know, overproduction in the US in the early 20th century led to widespread soil erosion and the Dust Bowl. The steady march of higher yields was achieved by using large quantities of fertilizers and pesticides, as well as by discarding local crop varieties that were deemed unfavorable. Farmland became concentrated in the hands of a few large players; the US had about one-third as many farms in 2000 as in 1900, and on average they were three times as big. In the same period, the proportion of the US workforce employed in agriculture shrank from slightly over 40% to around 2%. Supply chains have continued to be optimized for speed, reduced costs, and increased returns on investment.

Consumers have been mostly happy to enjoy the increases in convenience that have come with these trends, but there has also been a backlash. Products that are distributed globally can come across as soulless, removed from local culinary tradition and cultural contexts—we can find blueberries in the middle of winter and the same brand of potato chips in remote corners of the planet. As a reaction, more affluent eaters now look for "authenticity" and turn to food as an arena in which to declare their identity. Suspicions or outright critiques of technology have emerged within the so-called food movement, together with a frequent and uncritical embrace of pastoral fantasies that at times reflect the preferences of richer (and often whiter) consumers.

Such attitudes fail to acknowledge the obvious: the availability, accessibility, and affordability of industrial food has been a major force in reducing food insecurity around the world. The number of people suffering from undernourishment fell from around 1 billion in 1990 to 780 million in 2014 (though hunger is rising again—see page 74), while the world population grew by 2 billion in the same period.

And criticizing the mass production of food per se is misguided. It is indeed a very flawed endeavor that produces a lot of calorie-dense, nutrient-poor foods. But it is not doomed to ruin our planet and our well-being. Not if we make choices that take factors other than profit into account.

The value of values

The shutdown of slaughtering and meatpacking plants in response to covid-19 caused troubles upstream, forcing farmers to kill and dispose of livestock that were too expensive to feed without the certainty of sales. This is what happens when a system fine-tuned for efficiency, productivity, and profit collides with a shock.

Technology, however, is not inherently opposed to sustainability and resilience. In fact, many of the problems commonly blamed on technology in the food system derive from the legal and financial framework in which it develops. Intellectual property is a central issue here; patent owners have used their patents almost exclusively to maximize profit, rather than to improve food security and food quality.

Genetic modification is a great example. For the most part, its techniques have been applied to commercial crops such as wheat, soybeans, and corn, grown in huge quantities and traded internationally. The goal is single-minded: increase yields, even when that requires heavier use of pesticides and fertilizers—which are often patented by the same companies that own the patents to the GMOs.

That investment in genetic modification and agrotechnology is lacking, however, for many crops that function as staples for millions of smallholders around the world—from taro in the Pacific Islands, South Asia, and West Africa to cassava in Latin America and large areas of Africa. If applied to those crops in the pursuit of food security instead of profits, genetic technologies could be used to create stronger, more resilient local agriculture and a healthier food system—but they aren't, because that wouldn't generate profits large enough to interest the private biotech sector. To make matters worse, many low-income countries have also historically been forced to accept trade and financing deals from the IMF, World Bank, and World Trade Organization that open their markets to those heavily globalized commercial crops, regardless of farmers' or consumers' customs and needs.

And yet, most debates about GMOs focus on their supposed danger to human health—for which there is little scientific evidence—rather than on the way they tilt the playing field against small farmers and the communities they feed. In short, by focusing on spurious technological problems, we are ignoring very real legal and social ones.

The way forward, then, is in making choices that align technological advances with the causes of sustainability, resilience to shock, and people's well-being, instead of purely with the bottom line of large corporations. There are plenty of examples already. The Navdanya Community Seed Banks, initiated in India by activist Vandana Shiva, trains local practitioners (mostly women) to become seed keepers, making endangered varieties available to farmers who can then grow and cross-breed them. These low-cost conservation technologies help maintain agrobiodiversity by identifying, selecting, and protecting disappearing genetic material.

Food production and food security are so connected with food as a human right that technology and intellectual-property rights in this sector should work according to different principles from those in the rest of the tech world.

The question of ownership and control also touches other aspects of the entanglement between technology and the food system. There's a list a mile long of sleek gadgetry that promises to revolutionize the gritty work of conjuring food from the land (see page 50). Farmers can wire their fields with internet-enabled sensors, monitor their crops and livestock with agricultural drones, or manage inventory using a blockchain. They can use their cell phones to access data on weather, pests, and the cost of inputs and crops. But the incentives of the companies behind such innovations are to sell as many apps and devices and data streams as possible, not to feed and nourish as many people as possible. If the companies change their business model, discontinue a product or service, or simply fold, farmers are at their mercy.

Food production and food security are so connected with food as a human right—and so crucial for the survival of whole communities—that technology and intellectual-property rights in this sector should work according to different principles and priorities from those followed elsewhere in the tech world. For example, we could require tech companies to make their patents available in the public domain after a few years, or to share their royalty profits in exchange for access to new markets. Or we could require agricultural companies that develop new crops based on genetic material from plants found in specific communities to train members from those same communities to become biologists and technicians, while also sharing royalties with them.

There is already an international agreement mandating access to genetic resources and fair sharing of the benefits: 128 countries have ratified the UN-brokered Nagoya Protocol since it was adopted in 2010 (though the US, Russia, Brazil, and Australia notably have not). The aforementioned free-trade policies at the core of the WTO agreements, which have for decades hamstrung low-income countries, could be revised so that those countries can manage their food stocks and their import-export policies with an eye toward investing in local research and technology.

These are profoundly political choices. They should not be left to supposedly self-regulating economic mechanisms or to the quest for ever greater efficiency and productivity. Such priorities need to be balanced with others to ensure the greatest possible human benefit, rather than merely the greatest possible profit. That will require active participation from governments, activists, international organizations, research institutions, nongovernmental organizations, and representatives of local communities … the kind of authentic, democratic coalition that would please even the most demanding "food movement" devotee.

In the process, such cooperation could redefine how we assess new technologies and their use and impact. It may even leave us better prepared for the next crisis, whatever that may be.

Fabio Parasecoli is a professor in the Department of Nutrition and Food Studies at New York University.

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Reports from the front lines of food tech. **AS TOLD TO** *Krithika Varagur*

DISPATCHES

The notion of "food technology" may bring to mind fancy fake meats or hydroponic crops. However, to understand just how deeply technology permeates the food system, you have to see the many hidden innovations that produce the foods we eat at the prices we pay. In late 2020, Krithika Varagur spoke to people in the US, Mexico, and Kenya who help bring foods to market about the technologies they use daily.

Responses have been edited for length and clarity.

BEEF

IN SEARCH OF BOVINE PERFECTION

Artificial insemination, gene mapping, and DNA testing have revolutionized cow breeding.

JIM McADAMS
Partner, McAdams Cattle Company, and owner, 12 Bar Ranch
Seguin, Texas

Since last year, I've had some trouble with our calves' health. We're not sure what's going on. We think it might be extreme heat. You've probably heard of Certified Angus Beef, a real popular brand of meat—when you sell cattle that qualify, they will bring a premium. But one of the qualifications to get in that program is that they have to be from black-hide cattle, which are not as heat-tolerant as some other breeds. Mine are not 100% Angus, but they're about 75% Angus. And when it's real hot, we think those calves are just weak from the heat and they don't have the

PING ZHU; COURTESY PHOTO

vigor to get up and nurse. I lost some calves from heatstroke, I think, last year.

It's difficult for us to change our breeding program rapidly, but that's where we're benefiting from a lot of advances in technology and in research. "Seedstock" producers raise breeding animals, using techniques like artificial insemination and embryo transfer. These technologies are expensive, and it is not unusual for seedstock producers to sell their bulls to other ranchers for $30,000 or more. You'd be lucky to raise a hundred calves from a bull in his lifetime if you just turn him out naturally with the cows, but using advanced reproductive technologies enables that bull to sire several thousand calves.

Heterosis refers to the tendency for a cross-bred hybrid animal to often have better traits (like weight or longevity) than its parents. And it's a great tool for getting the breeds right. Basically, you have genetic differences in different breeds of an animal, and if you cross them, those genetic differences give you a bounce. The more distant the bloodlines, the more heterosis you're going to get. An example of how I use this in practice is crossing *Bos indicus* cattle, which evolved in the southern parts of the world, with our native *Bos taurus* cattle, in order to increase their heat tolerance and longevity.

Technology has spread like weeds in the ranching world. In the 1970s, artificial insemination became a widespread tool. In the 1990s, we also started to see modern techniques like gene mapping and DNA testing that help us balance our breeds. There is a cost to gene mapping because you have to test your animals, get them into a database, pay all these fees, pay for animal IDs, all of those things. But it lets us see which bulls have, for example, specific genes for growth. So it makes genetic progress for whatever our target is much faster.

The average cow's weight 50 years ago was probably 900 pounds. In the '70s, it was probably 1,000 pounds. Today, it's about 1,300 pounds. It takes more acres to maintain cows of that size. And they produce much bigger calves, and require more feed in the winter. In the '50s, in the early '60s, we got cattle too fat and too small, and their productive life was too short. Then in the '70s—I graduated college in 1972—there was this war on fat in the industry because the medical field had determined that eating too much fat was bad for people's hearts. We really focused on getting cattle that would be more efficient, bigger, leaner. That took us about 20 years. And we overdid it. We realized that we were losing the eating experience, because the meat was getting too tough. There's a fair amount of trial and error. Today, we're somewhere in the middle. I think we've hit the sweet spot. You won't really find yourself in a restaurant anymore saying, "I broke my tooth on that steak."

Breeding the right kind of cow has been one of the main interests of my career. It's a challenge, because the life cycle of a bovine is pretty long, compared to any other meat protein.

"THE AVERAGE COW'S WEIGHT 50 YEARS AGO WAS PROBABLY 900 POUNDS. IN THE '70S, IT WAS PROBABLY ABOUT 1,000 POUNDS. TODAY IT'S ABOUT 1,300 POUNDS ... BREEDING THE RIGHT KIND OF COW HAS BEEN ONE OF THE MAIN INTERESTS OF MY CAREER."

WALNUTS & ALMONDS

SHAKEN AND STIRRED

Tree shakers, mechanical sweepers, sorters, scanners, packers, and processors—along with water stress sensors—have changed how nuts get from trees to your mouth.

HAL CRAIN
Owner, Crain Ranch nut farm and processing facility
Los Molinos, California

I woke up at 4:30 today. Right now, the end of September, this is right in the middle of walnut harvest season. I'm still wearing my work clothes every day, going out into the field every day.

So the shaking operation comes first. You shake the trees, drop the nuts onto the ground. Then you have these mechanical sweepers that basically sweep all the nuts off the ground and into windrows, about three feet wide, all in a big, long line on both sides of each tree. Behind that goes a pickup machine, or a harvester, that picks them up off the ground, separates the dirt, sticks, and leaves, and puts them into trailers, leaving them much cleaner than what got picked up off the ground. Then from there, they get trucked to the huller, which removes the green husk off of the nuts that still have it on—30 or 40% of them—and cleans them and washes them. And the last phase is a dryer, where they go on these huge storage containers with forced air, heated air, being pushed through the storage containers to get the nuts down below 8% moisture.

Once that's done, then they're stable enough to be sent to the processing warehouse to be further processed, cracked, packed—whatever is going to be done with them. For the unshelled ones, which are about 95% of our

COURTESY PHOTO

output, we run them through processors with food-grade, natural cleaners, to try to make them as aesthetically pleasing as we can.

I'm a second-generation walnut farmer. In terms of how much mechanization has changed our work, it's been like going from the Model T to the Tesla, but in a much shorter time. I'm 51 now, and when I was a youngster they didn't even have a way to mechanically shake the trees. We would just get poles and knock [the nuts] out of the trees, or wait for them to fall, over months and months. Today, each harvest crew will pick over 500,000 pounds of nuts a day, versus about 2,000 pounds when it was mostly manual.

The processing, the packing, the sorting is all mechanical. Sorting out the defective nuts is all done via laser, with these WalnutTek machines by WECO, a company that specializes in electronic sorters. The ones being sold in-shell get scanned for shell defects. There are even ways to detect if a kernel is not full inside the shell. There are all kinds of other shell defects, like a partial husk or dark spots from sunburn that discolors the shell, which in turn means the kernel won't be very good quality. All of those defects are mechanically sorted. And plenty of other things, from insect damage to mold to shell particles. The human eye is the last factor before it goes into packaging, just to make darn sure that nothing is missed. Like if you have insect damage, you can visually see that.

We're in the far north end of California and it's going to reach 97 degrees today. It's low humidity. It's not desert by any stretch; we have significant rainfall. But we get really hot during the summer. We're just starting to use something called the FloraPulse, a plant water stress sensor, on our almond trees, which are about 10% of what we grow, and hopefully soon the walnut trees too. If I plug this device into a given tree and get a measure on that, I can adjust my frequency of irrigation to maximize tree health and crop longevity. Basically, the tree can tell me how thirsty it is. This is a big step in trying to actually get a direct measurement of plant stress and then identifying the parameters of what's ideal at certain times of the year.

Mechanized tree shakers allow crews to pick 250 times more walnuts per day.

MAIZE

WAITING FOR THE RAIN

Maize yields in sub-Saharan Africa are less than a third of what they are in the US, in large part because of drought. A new seed is helping farmers in Africa catch up with their counterparts elsewhere.

DORIS MONICA MUIA
Maize farmer
Machakos, Kenya

I've been a farmer for six years, mainly of maize, but also coffee and sweet potatoes. Two years ago, I started using a hybrid maize seed called SAWA, which was developed specifically for drought-like conditions by scientists from the International Maize and Wheat Improvement Center (CIMMYT), based in Mexico. It was first donated to me as a sample by Dryland Seed Limited, a local seed company, and now it's very popular, so a lot of us here buy it ourselves. This hybrid is better than the traditional varieties, no doubt; it's a better seed and yields a bigger crop. The taste is different too—it's a little sweeter. We eat a lot of maize in Kenya; it's our staple food, especially as *ugali*, a maize flour porridge.

We have two harvest seasons. October to December is the main one, and the minor one is February to April. If you come here in July or August, it is a very bad place to be. It's so hot. With this hybrid, even when we have small rains, the maize is very good. And they don't get so affected by the sun. The new variety has fewer diseases, including northern corn leaf blight, gray leaf spot, maize streak virus, and maize lethal necrosis, a viral disease

PING ZHU; COURTESY PHOTO

that was a big problem for us when it broke out in 2011.

It's early October and I am clearing the farm right now, and putting in manure from the cows. I am standing by, buying more seeds, and waiting for the rain. The selling price the government sets for maize is still not very good, unfortunately. But I still have more crops than some of my neighbors, who sometimes recycle seeds and don't have very much at all. With ordinary seeds, you have to take much more care of them for much less product. And none of us can really afford other inputs like fertilizer, so any other ways to make our land more productive is good.

CORN & SOYBEANS

CENSUS SENSIBILITIES

The Department of Agriculture counts America's crops and animals to figure out not just how many there are, but also how productivity varies throughout the supply chain.

JOYCE HELLE
Enumerator, National Association of State Departments of Agriculture
West Central Illinois

The National Agricultural Statistics Service is used to set nationwide estimates of agricultural commodities. We have 12 regions across the country, and ours is Missouri and Illinois. I and about 3,000 other folks across the country go out and collect data for the survey and meet with farmers face to face, or call them, or whatever it takes to collect the data. We are the ground troops who help estimate the size and scope of agricultural production in the country. Basically, we tell the whole world what the food production capacity is in the US; it's a way to continuously monitor the food supply chain so that there aren't huge price fluctuations like, for instance, with gasoline.

So here's what we did today—and it's not something we do every day. In Illinois they once had coal mines, which have since had to restore the land to its original status. So they have to plant corn, beans, or hay in those acres, and the yields have to come up to the county averages. And today I was out in some of those cornfields and I just walked throughout the field and picked samples. Today we tested two fields and there were 10 samples per field. For corn, we take samples from a 15-foot row, at different designated spots in each field, and weigh them. Then we take the third and fourth ears from that sample and send them to the lab in St. Louis and they work to come up with the yield. It's the same with soybeans, except we pick the beans from a three-foot section and send those samples directly to the lab. Those are the two major crops that I work with in the field.

Objective yield is one of a number of different indicators that help us set estimates for yield and production like that. For that, we are measuring the grain weight, the moisture content, the length and width of an ear of corn, and just a whole number of metrics like that surrounding a crop. And then that's plugged into a statistical model, which then spits out an indication as to what the yield is per acre. For another survey we do, we will just flat-out ask farmers, "What do you think your crop is going to yield this year, if you get normal weather conditions from now until harvest?"

PING ZHU; COURTESY PHOTO

> **“WE ARE THE GROUND TROOPS WHO HELP ESTIMATE THE SIZE AND SCOPE OF AGRICULTURAL PRODUCTION IN THE COUNTRY. BASICALLY, WE TELL THE WHOLE WORLD WHAT THE FOOD PRODUCTION CAPACITY IS IN THE US.”**

The biggest change that technology brought to my job was when we were issued iPads, starting around 2013. We now have two or three extra days in every survey period, because we’re not depending on the mail or UPS to physically get our data to headquarters on time; they are sent digitally. One other great thing I will say about the iPad is that a lot of times if an enumerator enters the data wrong, it will send up a little red flag and tell them, “Hey, you made a mistake.” So that has helped us a lot too.

POTATOES

THIS SPUD’S FOR YOU

Potato breeding hasn’t changed much for decades, but a change from asexual to sexual reproduction could open the way to many more new varieties with useful traits.

PETER IMLE
Farmer of potatoes, soybeans, and wild rice at Pine Lake Wild Rice Farms
Gonvick, Minnesota

GREG SMITH, GSMITHIMAGES PHOTOGRAPHY

The vast majority of the potato varieties grown today date back 50 to 100 years, which says a lot about the potato industry and the difficulty of breeding new varieties. Here, we strictly grow red potatoes, mostly for the East Coast and Florida restaurant markets. The number one thing that sells a red potato is a nice bright red skin color, without any blemishes.

We’re a seed potato farm, meaning we don’t buy material from outside our farm. We start out with very small sprouts, which we grow in test tubes before we transfer them to a greenhouse, where they’ll develop into plants that will create small tubers. Because that whole system is sealed, the potato tubers don’t carry any soil- or insect-vectored diseases. This also gives us the opportunity to collect new experimental varieties through that same system, side by side with our traditional stuff, so we’re evaluating new material every year. We do our own variety trials and experiment with new varieties in-house.

I’m an optimist by nature, and I’m always thinking that the next thing that we bring in is going to take the place of some of our long-term varieties. But in the 15 years I’ve been doing this, I haven’t found one yet.

Personally, I’m always evaluating for that even redder potato. I really thought we were very close with two experimental lines that we were working with the last three or four years, but last spring we went to plant them and the material had acquired a fair amount of seed rot over the course of the winter. Our end users were really complimentary of the variety, but unfortunately, it looks as though I can’t store it.

The biggest roadblock to breeding better potato varieties is that commercial potatoes are tetraploid, meaning that they have four sets of chromosomes. (A lot of other major crops, such as tomatoes and corn, are diploid, with two sets of chromosomes.) The reason this matters is that when you cross any two tetraploid potatoes, there is so much genetic variance in the offspring that unhelpful mutations can kind of hide. So traditional potato breeding programs, which work through trial and error, discard a huge amount, about 90%, of their offspring. It’s not a really efficient process.

Fifty years ago, when just about every land-grant university in the country had a potato breeding program, people were making significantly more crosses and evaluating significantly more material.

> **About 90% of novel potatoes in traditional breeding programs are discarded.**

Now that you’re down to just a handful of potato breeders left in the country, not enough crosses are being made and not enough material is being evaluated for that method to be successful, in my opinion. The Department of Agriculture recently funded a big grant for several breeders to come together and try to move commercial potato breeding from tetraploid to diploid. (I’m one of the advisors on that grant.)

There are several kinds of naturally occurring diploid potatoes. But it just so happens that over time, the most productive lines in North America were tetraploid ones, and those are most of what we still consume today. But the diploid lines that exist in nature are the starting point for this research. Moving potato breeding to diploid specimens would drastically decrease the time needed to create new potato varieties. Crossing diploids means that defective genes would have less room to hide, so to speak. Their offspring are much more predictable, so we could really select for desirable traits. And we could also plant them as true seeds, rather than as tissue cultures. Tetraploids are

“WE’RE STUCK IN THE PAST BECAUSE OF OUR RELIANCE ON COMPLICATED TETRAPLOID LINES AND THE DECLINE OF OUR AGRICULTURAL RESEARCH PROGRAMS.”

reproduced asexually, with replanted tubers, whereas diploids can be reproduced sexually, with pollinated seeds, and seeds are much easier to scale up for a new breed.

Many major crops such as corn already use hybrid diploid breeding, and we know a lot about the “parent” crops involved in any given cross. Using specific parents can produce a more targeted outcome, which can be any given characteristic that the breeder would like: yield, appearance, better shelf life, and so forth.

This is all on a long time horizon; I’m hoping to see this happen at some point in my career. It would have a big impact on seed potatoes, which currently take about five or six years until they become commercial lines. If it is successful, it would make available a lot of the genomic tools that other crops have been using for a long time to try and do more targeted breeding. I’m not talking about transgenics or CRISPR or anything like that, but the basic molecular tools used by most other crops today, like marker-assisted selection, which involves using genetic markers to identify particular locations in the potato genome that may be correlated to specific traits, and then using those to quickly identify parents and/or progeny that have these traits. (This is much faster than growing out multiple generations of material just to identify whether the traits are present or not.) Basically, we’re trying to move potato breeding into the 21st century. We’re stuck in the past because of our reliance on complicated tetraploid lines and the decline of our agricultural research programs. We’re not trying to change the basic flavor or texture of potatoes. But these new genomic techniques, which *would* change the basic nature of potato breeding, will be necessary to meet the rising demand for varieties that are more efficient at water use, use less fertilizer, are more disease resistant, need fewer pesticides, and can be stored at cooler temperatures.

CHOCOLATE

BEAN THERE, DONE THAT

In Mexico, where chocolate was invented, automation has transformed the way multinational conglomerates process cocoa beans.

ROGELIO RODRÍGUEZ SOBERANES
Plant manager, ECOM Cocoa
Veracruz, Mexico

We get our beans from the Ivory Coast, Cameroon, Ecuador, the Dominican Republic, Peru, Colombia, and right here in Mexico. Since we are between harvests, we are in the middle of buying all the beans for next year. When we plan production for next year, we know exactly how many tons we need.

I started working here in 2003. Our capacity then was 7,000 metric tons per year, and now we are processing 40,000 metric tons per year. In 2010, we scaled up our cacao product output in a major way. Then in 2016, we started producing certain products, like chocolate-covered marshmallows and almonds, in-house, which was a really big change. We sell to many different customers here in Mexico like Hershey, Mars, and so on, and we have to be competitive. It’s very important to produce efficiently, because cacao products are commodities and the cost of production is the most important thing. If you’re not competitive, you’re out. Globally, ECOM handles about 10% of the world’s cacao; the Mexico plant alone processes about 1% of the global total.

The Mexico plant alone processes 1% of the global total of cacao.

There are many different processes happening in our facility, all of which are mostly automated now: roasting the beans, grinding sugar, melting cocoa butter, powdering cocoa, tempering, molding, packaging. We work with European machines, mainly. All the programmable logic controller systems [basically, the computers that tell the larger machine what to do] come from Siemens in Germany, and we also invested about $3 million five years ago in machines from Royal Duyvis Wiener in the Netherlands. That’s the biggest difference.

This plant started about 20 years ago with many old machines that ECOM bought from Nestlé, when Nestlé closed their outfit in Mexico, and their machines were almost 100% manual. Today, we basically have two operators in one control room watching all the windows and screens, and about 95% of our work at the plant is done with computers. So the cost of staff is lower now too. We have about 100 people in the whole facility. The size of the equipment has also changed; a big roaster 20 years ago may have had a capacity of half a ton, and now it’s five tons.

COURTESY PHOTO


NEW
AWARDS UP TO
$500K
INNOVATE
TRANSFORM OUR FUTURE
R&D FUNDING PROGRAM
The National Reconnaissance Office Director's Innovation Initiative (DII) Program funds cutting-edge scientific research in a high-risk, high-payoff environment to discover innovative concepts and creative ideas that transform overhead intelligence capabilities and systems for future national security intelligence needs. The program seeks the brightest minds and breakthrough technologies from industry, academia, national laboratories, and U.S. government agencies.
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Too much and

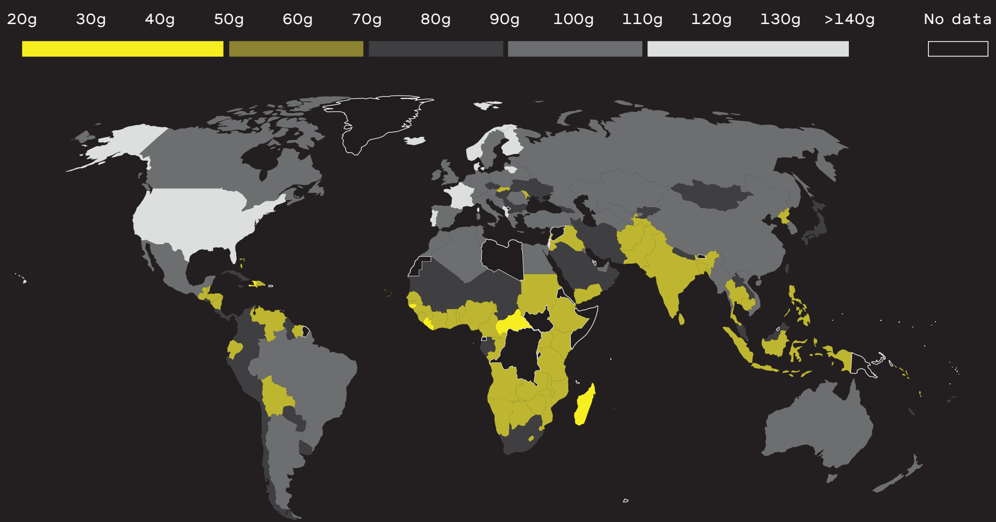
Our eating habits say a lot about us, and nowhere is that more true than in how we consume protein. Nearly a fifth of the world's population doesn't get enough of it, while people in richer countries take in far more than they need. People also tend to eat more meat as they get wealthier. That has big consequences for the environment: raising livestock requires huge amounts of land and crops and now creates nearly 20% of global greenhouse-gas emissions.

But people aren't necessarily fated to become carnivores as they rise from poverty. The United States and Europe have been stubbornly addicted to meat for decades, and China and Brazil have indeed upped their taste for flesh as their economies have grown. But India's population of over 1 billion people hasn't changed its meat-eating habits much.

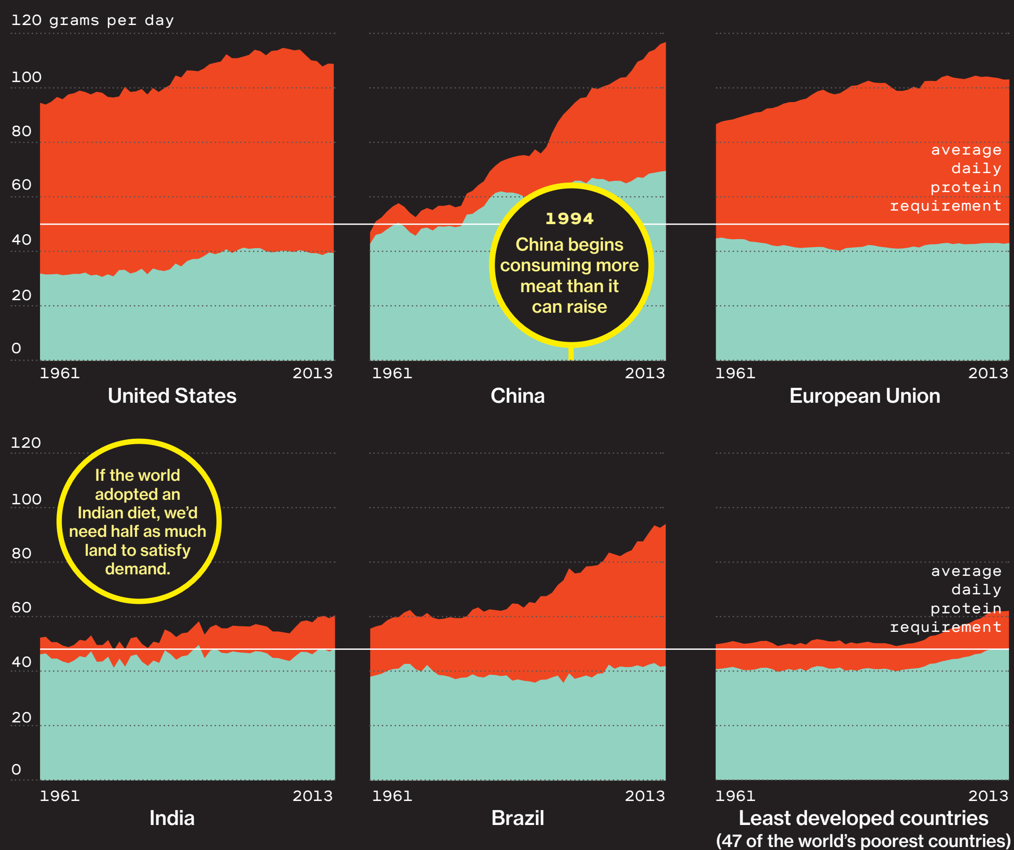
It's food for thought for any meat-eater. Greener alternatives like insects and cultured meat get a lot of attention, but they're still far pricier than commodity meats (and usually not nearly as tasty). Asking entire cultures to abandon meat isn't realistic. But neither is our current pace of consumption. We're going to have to trim from somewhere. *—Konstantin Kakaes and Emily Luong*

HOW MUCH PROTEIN THE WORLD EATS

Daily per capita protein supply, in grams (2017). The average person needs about 50 grams a day, depending on age, weight, activity level, and metabolism. Even in countries where the average is above this figure, many people are not getting sufficient amounts of protein.



HOW MUCH DIFFERENT COUNTRIES RELY ON ANIMAL-BASED AND PLANT-BASED PROTEIN



SOURCE FOR ALL CHARTS ON THIS PAGE: FOOD AND AGRICULTURE ORGANIZATION FAOSTAT. TIME SERIES DATA ENDS AT 2013 BECAUSE OF A CHANGE IN METHODOLOGY.

never enough

THE ENVIRONMENTAL IMPACT OF DIFFERENT KINDS OF PROTEIN

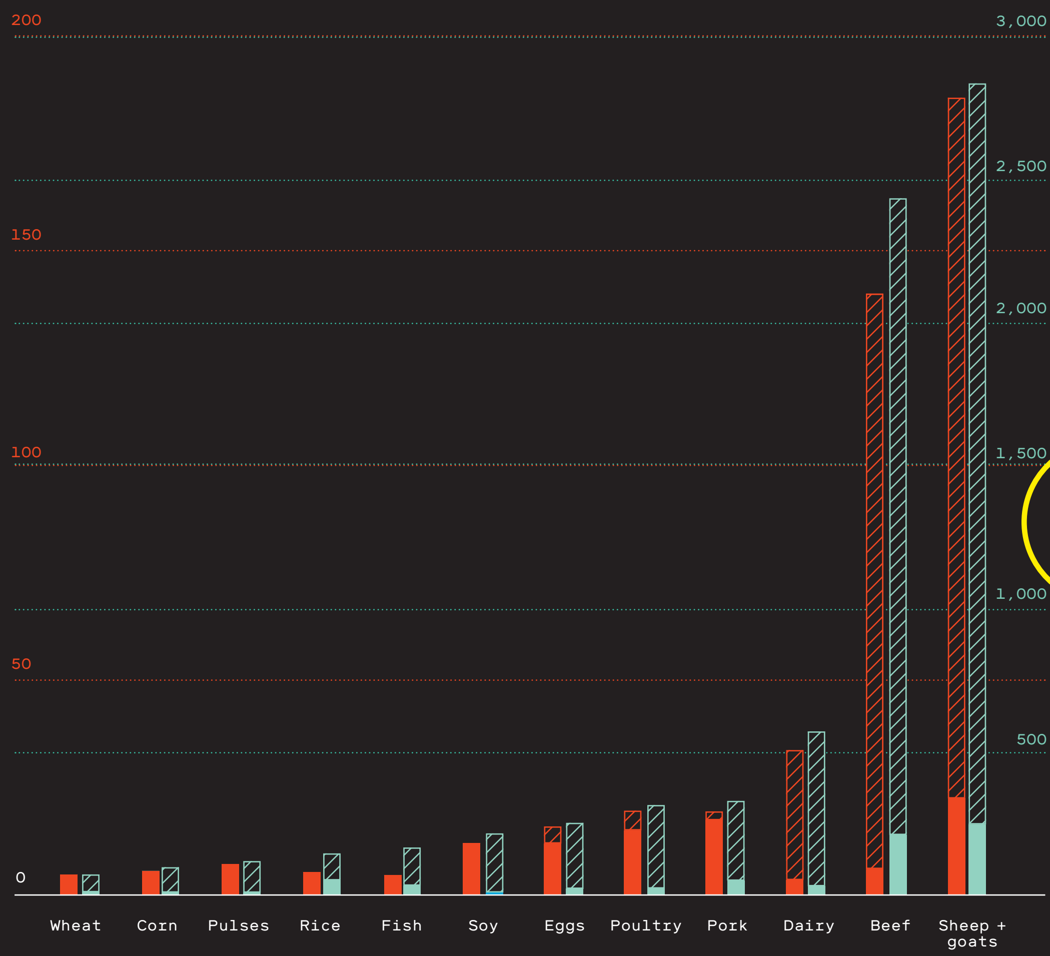
Producing meat is hungry work: it chews up crops and land, and generates huge amounts of emissions. Cattle, sheep, and goats make up the lion's share of the problem, which all comes down to a numbers game. Only 4% of the plant protein a cow consumes ends up as something a person can eat.

LAND USE
(hectares) per ton of protein

GREENHOUSE-GAS EMISSIONS
(tons of CO_2 equivalent) per ton of protein

Pasture
Cropland

Land-use change
Agricultural production



About
2/5
OF THE LAND ON EARTH (EXCLUDING ANTARCTICA) IS USED TO MAKE FOOD.

Food production accounts for about
1/5
OF GLOBAL GREENHOUSE-GAS EMISSIONS.

COST PER KG OF PROTEIN
Innovation ain't cheap


BEANS $1


SOY $2


WHITE RICE $2


CHICKEN $3

2012
The first year more fish are farmed than caught in the wild.


FISH $4


BEEF $5


PEAS $5


INSECTS $41


CULTURED MEAT $300

SOURCE FOR CHART: WORLD RESOURCES INSTITUTE (WRI) WORKING PAPER, "SHIFTING DIETS FOR A SUSTAINABLE FOOD FUTURE." SOURCES FOR COST PER KG OF PROTEIN: MCKINSEY AND WRI

HOW TECHNOLOGY REWRITES YOUR DIET

Wherever you live, the last meal you ate probably looked and tasted different from meals served in the same place 50 years ago. Your next meal will be shaped by the tools and techniques you use to prepare it. Whether we look forward or back in time, we can see how new technologies change what and how we eat. The following experts describe some advances that have had a large impact on our food system, and others that will transform it again in the years ahead. —*Amy Nordrum*

NEW WAYS TO GET AROUND

Million Belay
General coordinator, Alliance for Food Sovereignty in Africa (Ethiopia)

Horses are still the main mode of transport for many people in rural Ethiopia. Lately, though, new transportation options have prompted people I know to try different foods and abandon others their ancestors had eaten for centuries. About four years ago, for example, the only road that runs to and from a rural community called Telecho was improved. Soon, buses started to come. The village's market grew bigger, and residents began drinking beer made at commercial breweries instead of from the barley they grew. Today, farmers there plant more eucalyptus to sell the timber to other communities. That has brought more money to Telecho, but also reduced the total number of crops produced there.

Residents began drinking beer made at commercial breweries instead of from the barley they grew.

PERSONALIZED NUTRITION

Christine Gould
Founder and CEO, Thought for Food (Switzerland)

Per capita global food production has increased for decades. But having more food doesn't mean people are better nourished. Diseases caused by unhealthy diets—such as obesity, diabetes, cancer, and cardiovascular disease—are the primary cause of mortality in much of the world.

One problem is that our scientific understanding of food is still rudimentary. At most, 150 biochemicals are listed in conventional nutrition databases. That's a tiny fraction of the tens of thousands of compounds found in food. Some describe the many that remain unknown as "nutritional dark matter."

I see potential in the emerging field of personalized nutrition, which aims to combine new knowledge about such compounds with insights from an individual's own genetics and microbiome to deliver customized dietary guidelines and plans. The goal is a world in which people are not just fed, but nourished.

COURTESY PHOTOS

FINE-TUNING THE FARM

Marta Antonelli
Head of research,
Barilla Foundation (Italy)

The challenge ahead of us is clear: Build a sustainable food system that can nourish a growing and increasingly urban world. I think precision agriculture will be a big part of the solution. With this approach, conventional farming practices such as watering and fertilizing crops are performed at the right place and time, and with the appropriate intensity. For example, irrigation systems that deliver water through slow drips cut water use by up to 60% compared with sprinklers. Finding more improvements like this will require a new technology "stack" for agriculture.

BUYING AND SELLING FOOD ONLINE

Catherine L. Mah
Canada Research Chair in Promoting Healthy Populations, Dalhousie University (Canada)

E-commerce has transformed the way people eat; covid-19 accelerated this trend. Apps and online payment services like Shopify helped many restaurants and retail food businesses stay open and gave customers a way to enjoy their favorite meals even while isolated at home. But the growth of e-commerce has revealed how governments struggle to ensure that the benefits of technological development fall to everyone. Our institutions have not created policies regulating online commerce in a way that protects the public interest. E-commerce has widened divides between smaller and larger companies, and between rural and urban consumers.

CRISPR CROPS

John Ruff
Chief science and technology officer, Institute of Food Technologists (US)

People throw out 1.3 billion tons of edible food each year, yet 821 million people went hungry in 2018. CRISPR, a gene-editing tool, can help us increase food production, decrease food waste, and enhance the nutritional value of the foods we eat. Already, scientists have used it to increase omega-3 levels in plants and reduce gluten levels in wheat. They've also developed non-browning apples, potatoes, and mushrooms that are less susceptible to damage during shipping and will keep longer on shelves and in refrigerators. Some are even creating drought-resistant rice and corn to protect our food supply against the adverse impacts of climate change—a need that will become more urgent with time.

Already, scientists have used CRISPR to increase omega-3 levels in plants and reduce gluten levels in wheat.

PACKAGING WITH LESS PLASTIC

Jocelyn Eason
General manager of science and food innovation, Plant & Food Research (New Zealand)

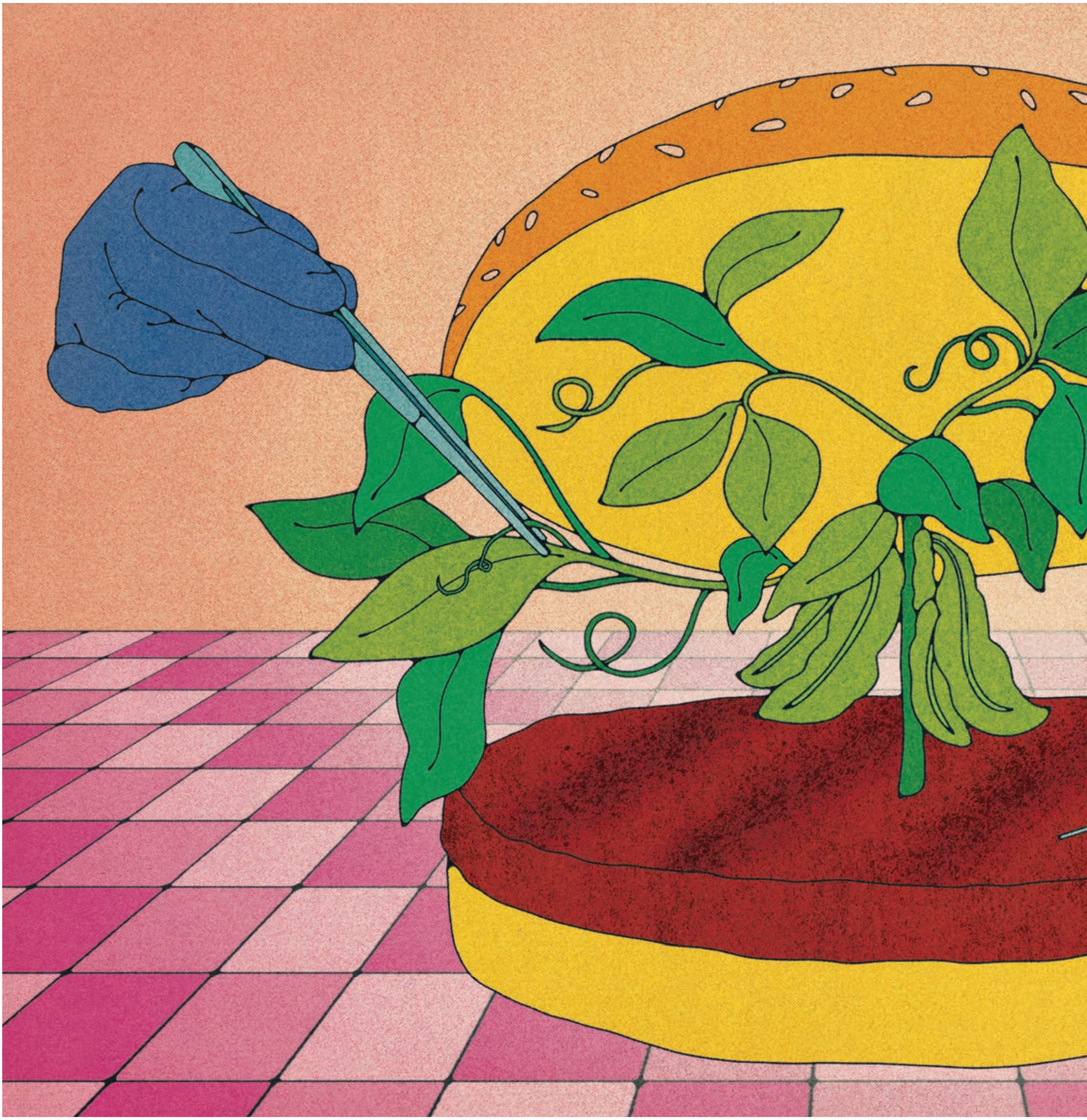
New packaging materials will allow many food producers to gradually move away from plastics, for good. During my lifetime, I've watched plastic become one of the biggest environmental hazards that we face as a society. Consumers want less of it in their lives, and regulators are beginning to ban or impose taxes on plastics used to package or serve food. Sooner or later, most producers will need to switch to more sustainable materials. Some alternatives are already available: Earthpac, a New Zealand company I've worked with, is using starch recovered from the wastewater of potato processing factories to make biodegradable trays, plates, and punnets (the small green baskets in which berries are often sold). Another client, Meadow Mushrooms, is making packaging from the stalks removed from mushrooms during processing.

FERMENTING AT SCALE

Jaime Romero
Associate professor in the Food Biotechnology Lab, University of Chile (Chile)

Fermentation is a powerful, natural process, and one of the oldest food preservation methods. However, it's only in the past 50 years that scientists have come to understand fermentation well enough to sustain it at scale. Fermentation can take many forms, but they all involve enlisting some kind of bacteria, yeast, or other microbes to chemically alter another ingredient (typically sugar). The acids produced during this process naturally preserve the resulting food. Fermentation can create thousands of different foods and drinks, including sake, kombucha, beer, wine, cheese, yogurt, pickles, sauerkraut, and sourdough bread. I think industrial-scale fermentation has expanded our options at the grocery store more than most of us likely realize.

CATHERINE MAH: GW SCHNITZLER; COURTESY PHOTOS



FLESH FORWARD

GROWING MEAT IN A LAB IS STILL WAY TOO EXPENSIVE. BUT MIXING IT WITH PLANTS COULD HELP FINALLY GET IT ONTO OUR PLATES.

One cool fall night 10 years ago, Jessica Krieger went for a run to clear her head. Krieger, then an undergraduate in neuroscience, had just watched a documentary that showed the gruesome ways many animals are slaughtered for food. "The animals were terrified, in pain, dying," she recalls.

Krieger was already worried about the meat industry's contribution to climate change, and the documentary convinced her to stop eating meat for good and become vegan. It also compelled her to try, in vain, to persuade her friends and family to do the same. But she wanted to do more—so she decided to get radical.

"I felt really helpless and hopeless about protecting animals and the planet," she says. "That wasn't a good feeling. So I preferred to pursue a crazy idea than do nothing."

By
NIALL FIRTH

Illustration by
Kate Dehler

Krieger threw herself into what at the time was a fringe area of biotech research: growing and harvesting edible animal cells without killing any sentient creatures. There had been a lot of talk—and some interesting results, including a lab-grown hamburger that cost as much as a house to create—but making a dent in the commodity meat industry was not remotely on the menu.

Today, though, things look a bit different. Cultured meat (or, if you prefer your high-tech foodstuffs seasoned with a bit more marketing savvy, “cultivated meat”—the industry now eschews phrases like “lab-grown” or “in vitro”) is already a nascent industry. The product is still exorbitantly expensive compared with old-fashioned meat, you can’t yet buy it at the supermarket, and for the most part it doesn’t look or taste much like the real thing. At least not on its own. That’s where the startup Krieger cofounded, Artemys Foods, comes in.

While lab-grown meat was busy trying to find its way out of the petri dish, plant-based meat substitutes were undergoing a revolution. Firms such as Impossible and Beyond Meat broke through to the mainstream by cleverly mimicking the flavor and texture of ground beef, pork, and chicken using vegetable proteins and fats. These days you can pick up an Impossible Whopper at Burger King and Beyond Meat sausages in supermarkets in dozens of countries.

That kind of competition could be seen as bad news for cultured-meat startups. But Krieger and a number of other entrepreneurs think it’s the opening they need to finally bring their creations to market—in the form of “blended meat,” melding the best of the plant-based and cultured-meat substitutes. Even the world’s biggest fast-food firms are interested: KFC has announced it will be working to produce blended chicken nuggets that could be available this year.

Regardless of who gets there first, blended meat is coming, and it might not be long before you get a chance to taste it.

TASTES LIKE CHICKEN?

In terms of industry buzz, cultured meat has never been hotter. At the end of 2016 there were just four firms working on it, according to a report by the Good Food Institute, the nonprofit that produced the documentary Krieger found so unsettling. By early 2020, that number had jumped to at least 55 startups around the world trying to re-create at least 15 different types of animal flesh, including pork, shrimp, chicken, duck, lamb, even foie gras.

The process for making these products has come a long way since Mark Post, a researcher at Maastricht University, had his $320,000 lab-grown burger cooked on television in 2013—but it essentially follows the same principles. A small sample of cells is taken from an animal, usually via biopsy, and then fed a broth of nutrients. When millions of new cells have grown, they are encouraged to differentiate into muscle cells and eventually strands of muscle fiber.

The technology’s promise is to reproduce the flavor and texture of meat without harming animals, and without the huge environmental costs of rearing them. Proponents also point out that cultured meat won’t carry diseases or need antibiotics, which breed drug-resistant bacteria.

Investors are biting. Memphis Meat, one of the biggest players, announced an infusion of $161 million in January 2020. It plans to open its first pilot factory in 2021 to produce its wares at scale (it has already created versions of beef meatballs, chicken, and duck). Many others, such as BlueNalu (fish) and Meatable (pork and beef), have also raked in substantial sums.

Another sign of the industry’s growing maturity is that a second tier of companies have sprung up to specialize in certain aspects of the process: developing better-quality growth media or novel bioreactor designs, for example, or just collecting and banking useful stem-cell lines from different animals. From the hype, the press releases, and the promotional videos—in which actors delightedly sample minuscule strips of flesh in fashionably lit restaurants and homes—it might seem as if the first cultured product is just months away.

But there’s a problem. The medium that nurtures the cells is expensive. The cost is dropping from the early days, when startups in the R&D stage relied on repurposed cell culture media taken from biomedical research. But growth media still make up the bulk of production expenses—estimates range from 55% to 95% of the total—and a kilogram of cultured meat still costs hundreds of dollars. Even allowing for eventual economies of scale as factories get up and running, it’s no recipe for success. No wonder, then, that cultured-meat firms have started thinking about how to get a piece of the huge market that plant-meat companies have opened up.

“When I was looking at the costs associated with 100% cell-based products, they were astronomical,” says Krieger. “And I also was becoming more and more impressed with the burgers that Beyond and Impossible

What's cooking?

Cultured- and blended-meat startups now come in many flavors.

Aleph Farms

Where ...... Rehovot, Israel
What .... Beef steaks grown on plant scaffolds
Funding ..... $14.4 million

Future Meat

Where ...... Tel Aviv, Israel
What .... Cultured fat
Funding ..... $16.2 million

SuperMeat

Where ...... Tel Aviv, Israel
What .... Chicken cells mixed with plants
Funding ..... $4.2 million

Cubiq

Where ...... Barcelona, Spain
What .... Chicken fat for blending
Funding ..... $17.8 million

Just

Where ...... San Francisco
What .... Cultured chicken
Funding ..... $300 million

Artemys

Where ...... San Francisco
What .... Plant & beef burger
Funding $125,000

Higher Steaks

Where ...... Cambridge, UK
What .... Pork products
Funding ..... $20,000 (seed)

Mission Barns

Where ...... San Francisco
What .... Plant & pork bacon
Funding ..... $3.5 million

Memphis Meats

Where ...... San Francisco
What .... Beef meatballs, chicken, and duck
Funding ..... $181 million

Peace of Meat

Where ...... Berlin
What .... Duck and chicken fats
Funding ..... $6.5 million

had come out with. It seemed like a natural fit."

Artemys, which has recently come out of stealth, expects to announce taste tests of the Artemys Burger any day now: a hybrid burger made from cultured beef cells mixed with plant-based proteins. Earlier this year the team ran an experiment, combining its cell-based beef with a store-bought plant-based burger. "It was really incredible," says Krieger. "It was like the missing link when it comes to meat alternatives." For her, the cells added "umami flavor" to the plant burger and increased its juiciness—all for a much lower price than a pure cultured burger.

That cost saving is also appealing for Benjamina Bollag, founder and CEO of Higher Steaks, a startup based in Cambridge, UK, that has been focusing on cultured pork. She says she's still deciding whether the firm will launch with blended products, but so far her team has experimented with making pork belly and bacon from a mixture of cultured pork cells and plant products. The pork belly was around 50% cultured cells, while the bacon was 70% cultured, says Bollag. The rest was mostly plant proteins.

Bollag and Krieger are unusual in the cultured-meat world in openly treating a hybrid or blended product as a welcome first step—desirable, even. For many, the mission to create 100% meat analogues from scratch is, ostensibly anyway, still paramount. Behind closed doors, it's likely a different story, however. "Even if they don't say it publicly, the vast majority of the cultivated-meat prototypes you may have seen in the news are in fact hybrid products," says Liz Specht, associate director of science and technology at the Good Food Institute.

Fast-food chains have no such idealistic notions about purity. In July, KFC announced that it was planning to start selling hybrid chicken nuggets: 20% cultured chicken cells, with the rest from plants. To make the nuggets, the company said, it is pairing with 3D Bioprinting Solutions, a Russian firm that in 2019 helped 3D-print a cultured-meat sample on the International Space Station.

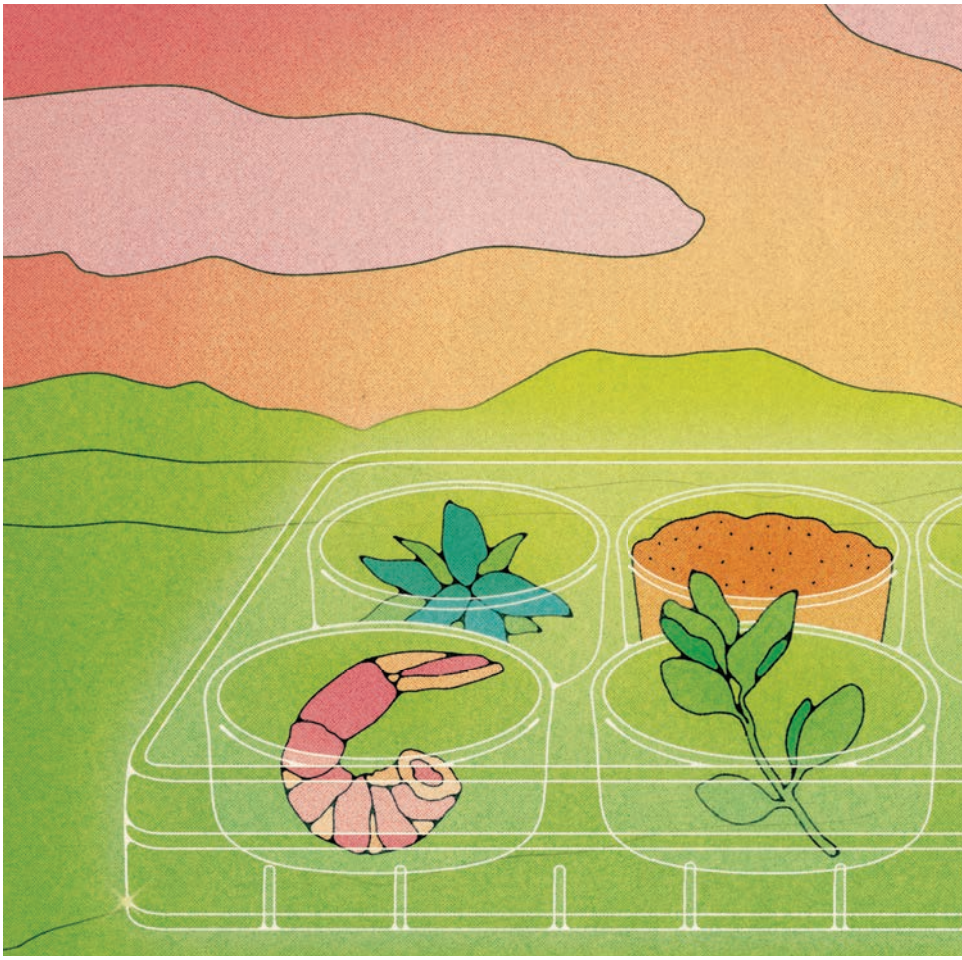
The nuggets will be created by first putting down a layer of extruded plant protein engineered to produce a more realistic meat-like texture instead of a kind of slurry. A layer of cultured chicken will follow, then another plant layer, and so on. Then this mixture will be shipped off to KFC's kitchens, where the nuggets will take shape and be coated in the Colonel's secret seasoning.

The first taste tests for the KFC blended nuggets are due to take place early in 2021. "The market is ready," says Yusef Khesuani, 3D Bioprinting Solutions' CEO.

MUSCLE MEMORY

If you think about it, there's nothing new about blended meat. Ground-meat products like sausages, nuggets, and burgers have always been a mashup (McDonald's has said one of its burgers can contain beef from over 100 cows), often mixed with breadcrumbs and other ingredients. That's because even conventionally produced meat is expensive. Bulking it out makes for a cheaper product that's still full of meaty flavor.

For big, traditional meat firms, that can be good for business and attractive to the growing number of people who want to eat less meat but aren't ready to give it up entirely. Tyson's "Raised and Rooted" line of sausages and nuggets blends real meat with pea proteins to appeal to such flexitarians in the US. And Perdue Farms has its own line of blended products that include "Chicken Plus" nuggets, voted the best nuggets in the US by the Food Network in 2020. The "plus" is plant material supplied by the Better Meat Company. "Think about it: the number one best-tasting frozen chicken nugget



in America is only 50% chicken," says Paul Shapiro, Better Meat's founder.

Shapiro believes foods like the hybrid nuggets will help cultured-meat companies get a foothold with consumers. "The first cultivated-meat products on the market will be blended," he says. "That's what I'm predicting. Cultivated meat is still hundreds of dollars a pound. Better Meat Company formulas are closer to $2 a pound."

But besides cost, there's another reason for blending cultured meat with plants. Meat is mostly muscle, but from a flavor perspective, muscle is a relatively minor player. When you bite into a piece of meat you encounter fats, connective tissue like collagen, that juice dripping down your chin … it's all part of the sensory experience. Eating pure muscle tissue—which is what most cultured meats are right now—is liable to feel like gnawing on a hunk of shoe leather.

This is where the advances in plant analogues can help. Scientists at Impossible and the Better Meat Company have perfected techniques for adding ingredients like coconut oil and sunflower oil to create moisture in their burgers and sausages. Plant ingredients, used expertly, can help make early cultured-meat products taste and feel more like the real thing.

"We're able to enhance that chew so when you bite down you get that pushback and satiating feel of biting into a piece of meat," Shapiro says.

That's important, because there are an awful lot of meat-lovers like me who will need to be convinced. And for the moment, plant-based products could still do with a helping hand in one crucial area of the gustatory experience.

FAT: WHERE THE FLAVOR'S AT

Ah, fat. Villainized for decades, it's still avoided by many of the health-conscious among us. But true foodies know that it's responsible for so much of what we love about food. In her hymn to good cooking, *Salt, Fat, Acid, Heat*, the chef and writer Samin Nosrat describes fat as the element that "carries flavor."

"Without the flavors and texture that fat makes possible, food would be immeasurably less pleasurable to eat," she writes.

For all the terrific advances by the likes of Impossible, plant-based meats that substitute plant fats for animal tissue get close but don't quite convince the palate. Call it a fatty uncanny valley.

That's why some cultured-meat startups have turned their attention, for now, away from trying to reproduce an entire hunk of meat from scratch and toward the aspects of meat that impart the most flavor.

Fat is the focus for Peace of Meat, a startup based in Antwerp, Belgium, that aims to provide high-quality cultured fats, particularly duck and chicken fat, to other players in the industry. The company's biologists extract stem cells from a fertilized chicken egg, cultivate them, and then grow fat cells in a bioreactor.

"The protein part of plant-based meats is actually pretty good," says founder David Brandes. "But when you bite into it, you suddenly feel like it's soy. Those products are missing the magic ingredient: animal fat. That's what drives texture and flavor."

MAKE NO MIS-STEAK

One evening in early October my wife and I went to Hawksmoor, a steakhouse in central London. It was our wedding anniversary and our first night in a restaurant since the pandemic lockdown began. For all the very many good reasons to eat less meat (environmental, ethical, health), steak still has that special-occasion tag. When it came, the T-bone we chose was beautifully charred from the grill on the outside, and pink, sweet, and succulent inside. It was juicy, packed full of flavor—in a word: heaven.

Cultured meat is years, if not decades, from delivering anything that approaches such an experience. Most cultured prototypes are closer to

the consistency of ground meat. But if and when something approximating a real steak hits your plate, there's every chance that it will be a hybrid.

In November, Krieger left Artemys to found a new blended-meat startup, Ohayo Valley. Instead of a burger, Ohayo Valley will be working on making a full steak, complete with marbled fat, out of a combination of plants and beef cells. She says she hopes to have the first taste tests of the steak later this year.

Just, a firm based in San Francisco, is working on chicken nuggets that were granted regulatory approval to be sold to consumers in Singapore in November. Eventually, it plans to create a full chicken breast made of nothing but cultured meat. Like my steak, a chicken breast gains its shape and texture from a complex mix of elements, including collagen, elastin, and tendons. Re-creating all of this in a bioreactor is no simple task.

"A 100% product would be an amazing thing, and I believe we will get there—it's just a lot more difficult," says Nate Park, the firm's director of product development and a former gourmet chef. In the meantime, Park and his team are working with edible, plant-based scaffolds that can act as connective tissue. "We have these beautiful systems we already understand," he says. "We can take our cultured mass and apply the two things together. It's like a chocolate-and-peanut-butter situation."

This is also the vision of Israeli firm Aleph Farms. Its proof-of-concept steaks, first shown at the end of 2018, don't look quite ready to take on my Hawksmoor T-bone—but they're recognizably meat, at least. Aleph, which partnered with 3D Bioprinting Solutions on the stunt aboard the International Space Station, expects to open its first production plant by the end of 2021, according to CEO Didier Toubia.

Toubia says the trend toward blended products is here to stay. "I believe in convergence," he says. "There will not be competition between plant and cultured meat; there will be collaboration and integration between the different solutions."

FINGER-LICKIN' GOOD

The Good Food Institute's report estimates that cultured products will compete with certain premium meats, like bluefin tuna or foie gras, within the next three years. By the 2030s, hybrid products might be able to undercut the cost of conventional meat, especially as the plant-based-meat industry grows in parallel, according to Specht. An analysis by management consultancy Kearney estimates that cultured meat, in some form, could take as much as 35% of the global meat market by 2040. The dream of animal-free meat is, it would seem, getting closer to reality.

It's clear that blended products will have to pave the way. But even ignoring the substantial technical obstacles that remain, a big question looms: Will consumers like these foods? The image of meat grown in giant vats, monitored by scientists in lab coats, has a distinct sci-fi ick factor that doesn't compete well with the cachet of organic, farm-to-table meat from animals that have spent their lives dancing in pastoral bliss.

Blended meat might, then, do one final job for the cultured-meat industry: help it gain acceptance. People who are already pretty comfortable with the idea if not the flavor of plant burgers will soon get to try them with a sprinkling of cultured cells to add some extra meaty oomph—an Impossible Plus, perhaps. Many of the people I spoke to suggested that this might win the average customer over more easily than an entire lab-grown meat product.

That's the hunch Krieger's been working from ever since her run that night. And it's one more and more people in the industry share.

"Facts alone don't change people's behavior," says Shapiro. "We didn't stop exploiting horses because we cared about horses; we stopped using them because new tech came along that rendered their exploitation obsolete. We're not going to stop causing the enormity of harms we do to animals because we care about chickens and pigs—it's going to be because we create a new technology that renders the current system obsolete."

That system of raising and then slaughtering animals has stood for millennia and won't be easily upended. Cultured meat—first blended, and then in pure form—will only stand a chance if it tastes at least as good as traditional meat. Krieger, for one, is gung-ho. "I think there's going to be a huge shift in consumer perception once people actually get to try cell-based products," she says, "and realize they taste amazing."

Niall Firth is the news editor of MIT Technology Review.

MOTHER'S

MILK

MANY PARENTS RELY ON INFANT FORMULA TO FEED THEIR NEWBORNS. COULD CELL CULTURE TECHNOLOGY PRODUCE SOMETHING CLOSER TO HUMAN BREAST MILK?

BY *Haley Cohen Gilliland*
ILLUSTRATIONS BY *Amrita Marino*

On a summer day in 2013, Leila Strickland sat, rapt, in front of her laptop and watched on screen as Mark Post unveiled the first lab-grown hamburger. To create the pinkish, flat patty, Post, a professor of vascular physiology at Maastricht University in the Netherlands, had taken thousands of tissue culture plates full of bovine stem cells, mixed them with fetal calf serum and other nutrients, and waited until they differentiated into muscle cells. This was exciting in and of itself. But Strickland's mind wandered to another potential application of cell culturing: human breast milk.

Like many mothers, Strickland had hoped to breastfeed both her children for the first six months after they were born.

The medical establishment considers breastfeeding the gold standard of infant nutrition, reducing the likelihood of digestive problems, rashes, and—most compelling—necrotizing enterocolitis, a rare but potentially fatal intestinal disease in premature infants.

But like many mothers, Strickland had found breastfeeding difficult. Her first child, a son born three years earlier, had struggled to effectively latch onto her nipple; when he did, she felt searing pain. He began to lose weight. She had spent all day, every day, nursing or pumping to stimulate her milk flow, and still her son cried, hungry. She was now experiencing similar issues with her infant daughter.

As Strickland watched Post from her kitchen table, she began thinking about how she might be able to use a process like his to grow not artificial beef but the cells that produce breast milk. "A pregnant woman could have a needle biopsy of her breast during pregnancy, and I could get the cells growing and producing milk before the baby is born," Strickland wrote excitedly in an email to a friend at the time.

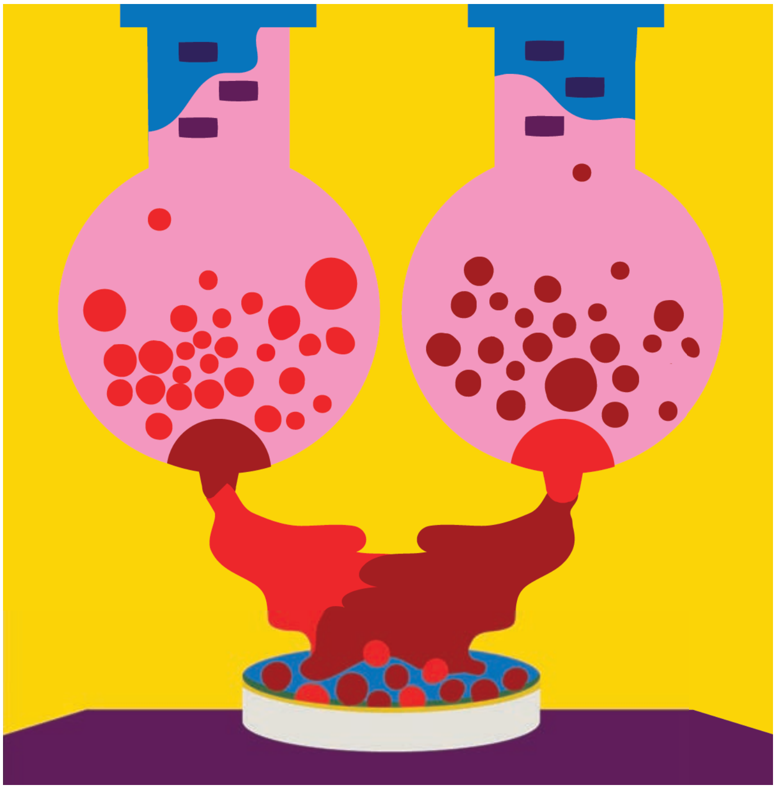
She had earned her doctorate in cell biology and spent several years as a researcher at Stanford before finding work as a medical editor and writer. This was a chance to turn back to the lab bench, with more independence than the average academic. A few days later, she and her husband scrounged together $5,000 in savings and purchased a hulking gray tissue culture hood, a microscope, an incubator, and a centrifuge from eBay for her to experiment with. "It was old dinosaur equipment—most of it probably from the 1960s," Strickland recalls.

For years she struggled to keep the project funded, and she came close to abandoning the idea. But in May 2020, Biomilq, a company she had founded, got $3.5 million from a group of investors led by Bill Gates. Biomilq is now in a race with competitors in Singapore and New York to shake up the world of infant nutrition in a way not seen since the birth of the now $42 billion formula industry.

Breastfeeding has swung in and out of vogue since ancient times—influenced by the evolution of medical knowledge, but also by race and social status. Wet nursing, the outsourcing of breastfeeding to someone other than a baby's mother, goes back at least to ancient Greece. Before the Civil War in America, white enslavers forced Black women to breastfeed the enslavers' children, often to the detriment of the women's own infants.

In 1851, the first modern feeding bottle—an elaborate contraption with a cork nipple and ivory pins that selectively closed inlets to regulate air flow—was invented in France, pushing wet nursing to near extinction. Shortly thereafter, German chemist Justus von Liebig concocted the first commercial infant formula, which consisted of cow's milk, wheat, malt flour, and a pinch of potassium bicarbonate. It quickly came to be considered the ideal infant food.

By the 20th century, formula use had skyrocketed, driven in large part by zealous advertising to doctors and consumers. A 1954 advertisement for Carnation evaporated milk in America shows a radiant mother and infant with text that reads, "8 out of 10 mothers who feed their babies a Carnation formula say: 'My doctor recommended it!'" Later, formula companies began giving hospitals free formula to distribute to new mothers. At the same time, more women were joining the workforce, making sustained breastfeeding more complicated. The perception that formula was just as safe and efficient, if not more so, led breastfeeding rates to plummet. By 1972, 22% of American infants were breastfed—a historic low, down from 77% of those born between 1936 and 1940.



"I PAID A GUY $20 TO SLICE THE UDDER OFF OF A FRESHLY SLAUGHTERED COW."

Today, those rates have rebounded, and doctors widely agree that breast milk provides the best nutrition for infants. Most American babies—about 84%, according to statistics from the Centers for Disease Control and Prevention—are breastfed at some point. But only one-quarter are fed solely breast milk for six months, as recommended by the American Academy of Pediatrics and the World Health Organization.

Breastfeeding isn't always easy. As Strickland experienced, babies can struggle to latch on; sometimes the breasts don't produce enough milk; and it can be excruciatingly painful for the mother.

Moreover, many mothers of newborns have to work, and it can be difficult if not impossible to breastfeed or pump milk in the workplace. This, obviously, is harder for women who are poor, and especially in countries like the United States, where there is no mandatory paid parental leave and only a small percentage of working mothers get it from their employers.

The first step Strickland took toward creating breast milk in the lab was less than glamorous. She couldn't afford to buy human mammary cell lines, which can cost hundreds or even thousands of dollars. Instead, she decided to start with cells from cows. To begin her experiments, she needed to find cells—lots of cells—and cheaply.

One weekend in February 2014, Strickland put a cooler, some ethanol, and sterile instruments in the trunk of her car, stuffed a wad of $20 bills in her pocket, and drove down the tree-lined North Carolina interstates to Randolph Packing, a family-owned meat processing company in Asheboro that operated out of a stocky brick warehouse on a residential road.

The manager led her to the processing area, where recently slaughtered cows were strung up by their hooves and moved along a conveyor belt for processing. Trying to keep her eyes locked on the ground, she pointed up at a cow's udder and muttered weakly: "I'd like that piece, please." She went back to her makeshift lab, placed a piece of udder in a petri dish, doused it with amino acids, vitamins, minerals, and salts, and carefully deposited it in an incubator.

In a message to her parents, the next day, she wrote: "I went to the slaughterhouse yesterday and paid a guy $20 to slice the udder off of a freshly slaughtered cow… It's safe to say I won't be eating any beef for a while. Came in this morning and found that the cells are growing! A cow died yesterday morning, but a piece of her is still alive in my lab!"

Breast milk derives from two types of cells in the milk ducts and alveoli—small sacs in the mammary gland where milk collects. Luminal epithelial cells absorb nutrients from the bloodstream and convert them into milk. Beside them, lining the ducts and alveoli, are smooth, muscle-like myoepithelial cells. When an infant starts suckling, it prompts the myoepithelial cells to contract, pushing milk from the luminal cells, through the ducts, to the baby's mouth.

For three years, Strickland brought her laptop to her tiny rented lab space so she could run experiments with her cow udder cells between writing and editing assignments. Her biggest triumph was persuading the luminal epithelial cells to form a continuous layer that could maintain the compartments critical for synthesizing milk. She figured out which surfaces promoted the healthiest cell division and how the density of cells affected their growth rate. None of these findings were novel, but she was pleased to be learning the techniques needed to ultimately move on to human cells.

By 2016, Strickland had run out of money and had to put the endeavor on hold. But the idea never left her. Eventually, in 2019, as more and more cultured-food businesses began trying to make everything from meat to fish to chicken nuggets in a lab, several friends convinced her to revive her plan.

Strickland recruited two other scientists to work with her. In August 2019, they were accepted to IndieBio, a prestigious biotech accelerator in San Francisco that gives startups $250,000 of seed funding and other support. She quit her day job and began to work on the project full time.

There was a problem, however. Strickland and her two partners all came from similar backgrounds, with extensive scientific experience but limited business bona fides. As the team prepared to move to California for four months, it became clear they were not a good fit.

Around the same time, a friend introduced Strickland to Michelle Egger, a food scientist in her late 20s. Egger had been fascinated with milk since she was a child growing up in Minneapolis, where she once placed second in a youth butter carving competition at the Minnesota state fair. After college at Purdue, Egger got a job in the dairy department of General Mills, where she worked for three years before enrolling in business school at Duke. She was in her second year when she first met Strickland.

Egger was excited by Strickland's proposition. Most infant formulas consist of environmentally intensive dairy products that require ample water to manufacture and prepare. Palm oil is another common ingredient. One study in 2015 suggested that producing one kilogram of milk formula generates the equivalent of four kilograms of carbon dioxide emissions. Strickland's approach had the potential to be much more efficient.

Things were hard at first. The change to the team caused Biomilq to lose its spot at IndieBio. It applied for, but failed to secure, several research grants. Worried that Biomilq would run out of money, Strickland started speaking to her old boss about returning to the job she'd left. Egger also quietly began to look for jobs.

Biomilq was on the brink of shuttering when Strickland and Egger were promised $3.5 million in funding from a group of investors led by Breakthrough Energy Ventures, which Bill Gates had established to back technologies that could reduce carbon emissions. Upending the formula industry held the promise of doing just that. As the spring of 2020 gave way to summer, the money arrived in Biomilq's bank account.

Biomilq is not the only company aiming to make a new kind of baby formula. Using a broadly similar approach, TurtleTree Labs in Singapore eventually hopes to "replace all milk currently on the market," according to cofounder Max Rye. In addition to other projects, the company is working to create "fortifiers" that can be added to formula to duplicate the properties of breast milk. Some formulas are already fortified with proteins and carbohydrates derived synthetically or from cow's milk. Another cofounder, Fengru Lin, explains that, in contrast to Biomilq, TurtleTree plans to work with the formula industry and hopes to get its products to market in 2021.

Meanwhile, Helaina, a company based in New York, will emulate breast milk through fermentation. Laura Katz, the company's founder, plans to use microbes to synthesize the milk's constituent compounds—proteins, carbohydrates, and fats—and then recombine them into a nutritious liquid. Since similar processes have already won approval from the US Food and Drug Administration for products like Impossible Burgers, which are made from fermented soy protein, she hopes to face fewer regulatory hurdles than her competitors. Like Strickland and Egger, she is motivated by indignation at the lack of options for new parents.

"I think the best thing we can do is support women to breastfeed," Katz says. But if that's impossible, mothers "deserve something better than current infant formula." She adds, "I see all this innovation happening in cell-based meat production for people who just want to eat a burger, but the products that we feed babies have stayed static over the past 20, 30 years."

None of these propositions will be scientifically simple, in part because relatively little is known about breast milk. Most studies of human mammary epithelial cells tend to focus on their role in breast cancer rather than milk production.

As for the milk itself, it's a rich and bewildering stew of thousands of chemicals. "We know nutritionally about the proteins, the carbohydrates, and the fat in there. We know about some particular bioactive molecules in there, like oligosaccharides [complex sugars that feed healthy bacteria in a baby's gut], IgA [the main antibody found in breast milk], bile-salt-stimulated lipase [an enzyme that aids in the digestion of fats]—these things that people always bring up as being good in breast milk," says Tarah Colaizy, the research director of the Human Milk Banking Association of North America, who also teaches at the University of Iowa. But, she notes, breast milk also contains short strands of RNA, whose presence was only discovered in 2010, and whose role in infant development is not yet well understood.

That's why Strickland and Egger plan to use mass spectrometry, a technique that measures the mass of different molecules within a sample, to study how the proteins, oligosaccharides, and fats contained in their product compare with the constituents of human milk pumped from a breast. But another challenge looms even larger: how to standardize a substance that is unique to every mother.

Breast milk changes in composition as a child grows. For the first few days after giving birth, mothers produce colostrum, a thick, yellow, concentrated milk packed with compounds like the antibody IgA and lactoferrin, an abundant protein that boosts a baby's immunity. Soon, colostrum is replaced by "transitional milk," which is thinner but contains more fat and lactose. After about two weeks, a mother's milk is considered "mature." But even then, it can change in composition over the course of a single feeding. Hindmilk, or the last milk left in a breast, has a higher fat content than the milk that is produced earlier on, which is why women are often counseled to empty one breast before switching to the other.

Though Egger and Strickland admit they won't be able to replicate this complexity, nor all the antibodies and microbes in any given woman's milk, they say their product will be more personalized than those of their competitors. Just as Strickland envisioned back in 2013, they plan to work with pregnant women, taking samples of their mammary epithelial cells and culturing them to create individualized milk for use when their babies arrive. After that, they hope to create a more economical generic option using donor cells. Both, Egger insists, will be better than formula.

"I SEE ALL THIS INNOVATION IN CELL-BASED MEAT PRODUCTION ... BUT THE PRODUCTS THAT WE FEED BABIES HAVE STAYED STATIC."

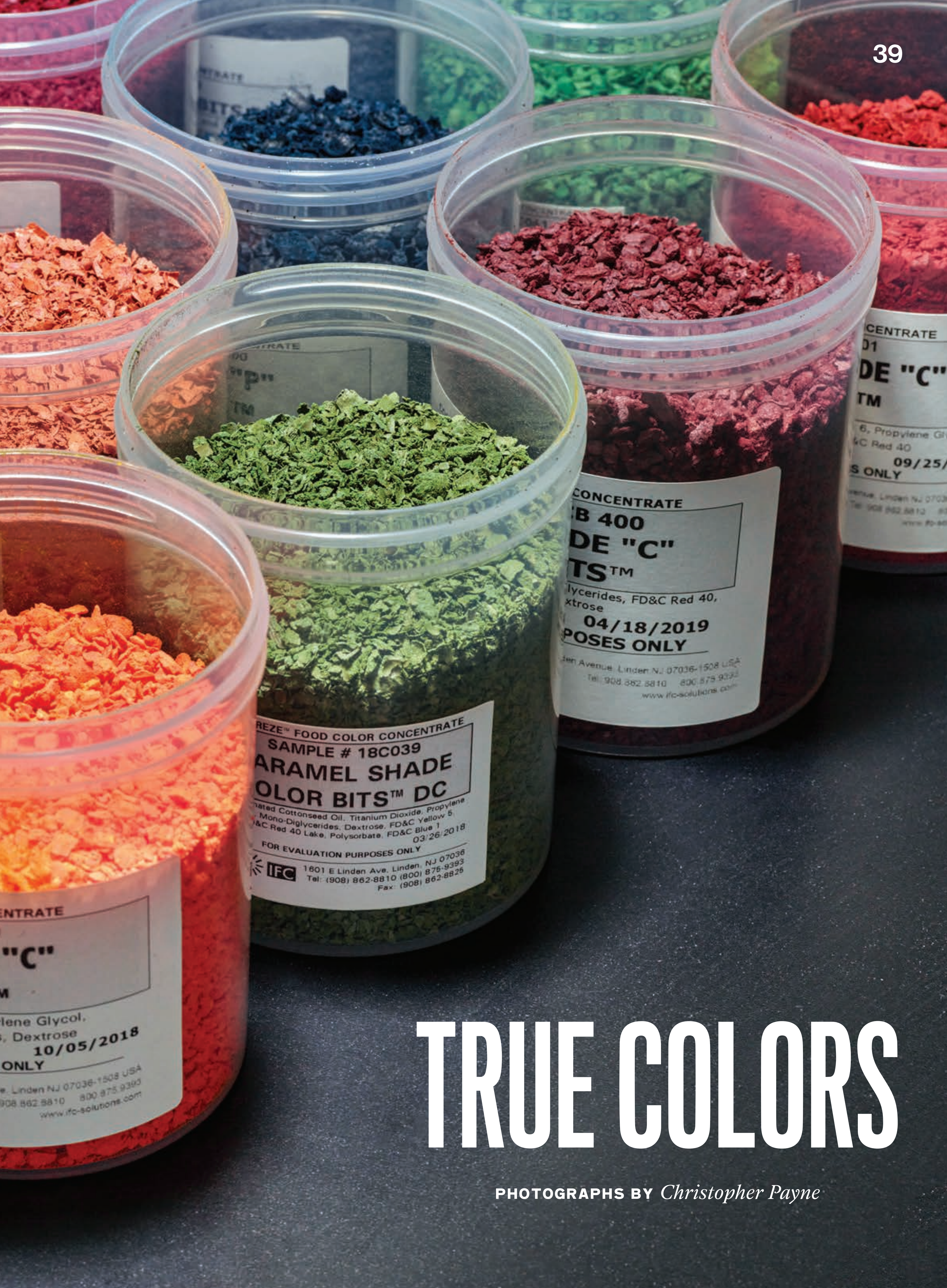
The Biomilq researchers are now working from a whitewashed lab space in Durham, North Carolina, that they share with several other biotech startups. In a freezer set to -80 °C (-112 °F), they store test tubes full of cells from a number of different donors. Some of them, like those from a 27-year-old woman who donated her mammary tissue after a breast reduction surgery, have been "immortalized"—manipulated to proliferate indefinitely.

Strickland and Egger have already produced a liquid containing both lactose and casein—the main protein and sugar compounds found in breast milk. They are now testing it to see if they can detect other components, like oligosaccharides and lipids. They are currently tinkering with their equipment and the nutrients they use to grow the cells to see what combination gets them closest to matching the composition of natural breast milk; they estimate it will take about two years to come up with a good enough match.

One Friday morning in September, Strickland took a test tube containing 3 million cells, warmed it between her hands, and spread the contents over a plastic tissue culture plate. A colleague then doused the plate with a warm yellow liquid containing 53 different salts, vitamins, minerals, and amino acids. Once the plate's surface was mostly covered with duplicating cells, they planned to move the cells into a small bioreactor, a plastic device with clear tubes emanating from its sides that encourages growth. After about a month, the cells would begin to secrete a substance similar to breast milk. There's only one small problem, Strickland says. "We don't yet know what to call it."

Haley Cohen Gilliland is a writer based in Los Angeles.

IFC Solutions in Linden, New Jersey, makes both natural and artificial food coloring in “almost any desired shade,” according to the company. This variety of colors would have been tough to imagine in the mid-19th century, when the first artificial food color (purple) was produced from coal by-products. These “Color Bits” are prized by candy manufacturers because they are easy to mix into hot masses of candy but are low in moisture, which makes for a long shelf life.



TRUE COLORS

PHOTOGRAPHS BY *Christopher Payne*

Color Bits are made by oversaturating liquid colorants (left) and then adding a thickening agent, like corn sugar (right). Once the resulting cake dries, it is chopped into bits (see following pages).

Scarlet Shade Red C (left tray) and Striping Red C (right tray) both get much brighter once diluted. If you've eaten a candy cane in the US, the red stripe is likely to have come from a tray like the one to the right. Both are proprietary blends based on Red 40, a synthetic dye also known as Allura Red.


HOBART

LESSONS FROM THE PIG EPIDEMIC

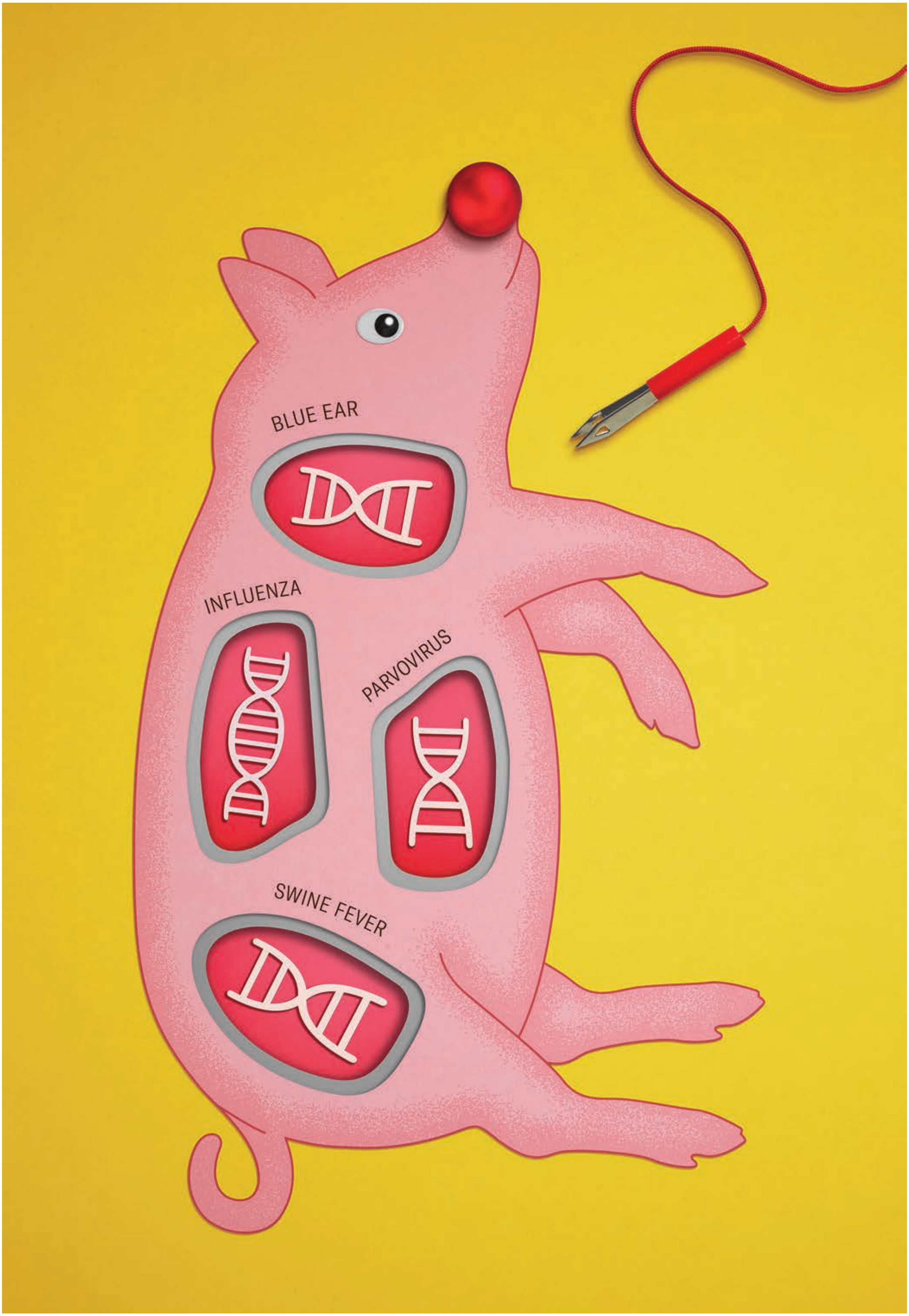
Gene editing
is being recruited in the fight
against outbreaks on farms.

By **ANTONIO REGALADO**

Illustrations
by **SELMAN DESIGN**

When covid-19 began to race around the world, countries closed businesses and told people to stay home. Many thought that would be enough to stop the coronavirus. If we had paid more attention to pigs, we might have known better. When it comes to controlling airborne viruses, says Bill Christianson, "I think we fool ourselves on how effective we can be."

Christianson is an epidemiologist and veterinarian who heads the Pig Improvement Company, in Hendersonville, Tennessee. The company sells elite breeding swine to the pork industry, which for the last 34 years has been fighting a viral disease called porcine reproductive and respiratory syndrome (PRRS).


BLUE EAR
INFLUENZA
PARVOVIRUS
SWINE FEVER

The pathogen causes an illness known as blue ear, for one of its more visible symptoms; when it first emerged, in the 1980s, it was simply called “mystery swine disease.” Once infected with PRRS (pronounced “purrs”), a sow is liable to miscarry or give birth to dead, shriveled piglets.

“And I’m going to say yes, it’s worse for pigs than covid is for us,” says Christianson.

To stop PRRS, as well as other diseases, pig farmers employ measures familiar to anyone who has been avoiding covid-19. Before you enter a secure pig barn, you get your temperature taken, shower, and change clothes. Lunch boxes get bathed in UV light, and supplies are fogged with disinfectant. Then there’s the questionnaire about your “last pig contact”—seen any swine on your day off? Been to a country fair? (Answering yes means a two-week quarantine away from work.)

Despite the precautions, the virus can slip in. Once inside, it quickly spreads in the close quarters. Swift “depopulation”—i.e., culling—of the animals is the most effective way to get rid of it. In bad years, American pig farmers lose $600 million to PRRS.

Now Christianson’s company, which is a division of the British animal genetics firm Genus, is trying something different. Instead of trying to seal animals off from the environment, it’s changing the pigs themselves. At an experimental facility in the central US (the location kept secret for security reasons), the company has a swine IVF center and a lab where pig eggs are being genetically edited using CRISPR, the revolutionary gene scissors.

During a virtual tour, a worker carried a smartphone through the editing lab into the gestation area, where sows spend nine months until giving birth—“farrowing” is the farmer’s term. Then he led the way to a concrete room where gene-edited piglets grunted and peered at the camera. According to the company, these young pigs are immune to PRRS because their bodies no longer contain the molecular receptor the virus docks with.

Every virus attacks cells by fusing with them and injecting its genetic cargo. With covid-19, the virus attaches to a receptor called ACE-2, which is common on airway and lung cells—the reason the disease causes problems with breathing. With PRRS, it’s *CD163*, a receptor on white blood cells. These experimental pigs don’t have a complete *CD163* gene because part of it was snipped away with gene editing. No receptor, no infection.

According to the company’s unpublished research, attempts to infect the gene-edited pigs with PRRS have not succeeded. “I never thought it would be a light switch,” says Christianson. “But it seems to work on all types of pigs and against all the strains of the virus.”

“I NEVER THOUGHT IT WOULD BE A LIGHT SWITCH. BUT IT SEEMS TO WORK ON ALL TYPES OF PIGS AND AGAINST ALL THE STRAINS OF THE VIRUS.”

Notoriously, a similar method has been tried in humans. In a disastrously reckless 2018 outing, Chinese scientists edited human embryos in hopes of conferring resistance to HIV, the cause of AIDS. Those researchers likewise dreamed of halting a disease by removing a receptor. The problem was the technology wasn’t ready to do such an ambitious job safely. Although the CRISPR tool is immensely versatile, it lacks precision, and the DNA surgery created something akin to genetic scars in the twins born from the experiment.

In September a high-level international panel said no one should try modifying babies again “until it has been clearly established that it is possible to efficiently and reliably make precise genomic changes without undesired changes in human embryos.”

But with pigs, the era of genetic modification is now, and its benefits might be visible soon. Genus hopes to win approval to sell its pigs in the US and China as early as 2025. Already, its experimental stations are home to hundreds of gene-edited pigs and thousands of their descendants—likely the largest number anywhere.

To Raymond Rowland, a researcher at the University of Illinois who was involved in creating the first PRRS-proof animals, gene editing is “in its largest sense, a way to create a more perfect life” for pigs and their keepers. “The pig never gets the virus. You don’t need vaccines; you don’t need a diagnostic test. It takes everything off the table,” he says.

Elite pigs

Aldous Huxley’s novel *Brave New World* begins with a tour of the “Central London Hatchery,” where children in a future society are being produced through a test-tube process under a sign that reads “COMMUNITY, IDENTITY, STABILITY.” The signs at Genus’s facilities are mostly about temperature checks and hand-washing, but the concept is not so different. Every pig is numbered, monitored, and DNA-tested for its genetic qualities.

The firm manages animals selected to be the healthiest and fastest growing, and to have the largest litters. These animals—what Genus calls “elite germplasm”—are then propagated via breeding on “multiplier farms” and purchased by producers everywhere from Iowa to Beijing, who breed them still further.

The company has been using DNA sequencing for several years to identify pigs with preferred traits and to steer its breeding programs. In 2015, it signed an exclusive license to gene-edit pigs and cattle using technology from Caribou Biosciences, a company started by Jennifer Doudna of the University of California, Berkeley, who last October shared a Nobel Prize for the development of CRISPR.

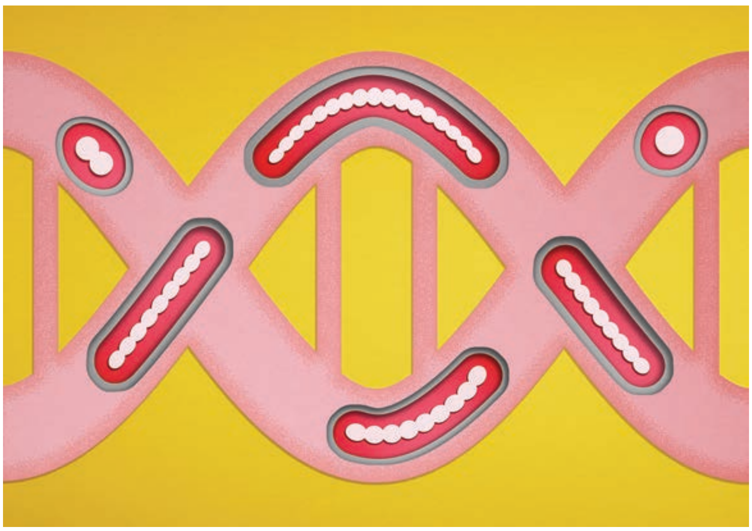
Because the pig company had no experience in genetic engineering, it began to hire plant biologists. One of them is its chief scientific officer, Elena Rice, a Russian-born geneticist who spent 18 years at Monsanto, mostly developing genetically modified corn plants to grow bigger and resist drought. "The plants were never emotional to me," says Rice. "The little pig or little cow—it's very emotional. You want to hug them; you want them to be healthy. It's like having a kid. You don't want them to be sick."

The Genus research station is set up to carry out the editing process quickly, on many pigs. Sows are anesthetized and then rolled into a surgical suite, where veterinarians remove eggs from their ovaries. The eggs are moved to the lab, where they are fertilized and the CRISPR molecules are introduced. Two days after editing, the embryos—by then a few cells big—are implanted into surrogate sows.

CRISPR is renowned for its ability to cut DNA at predetermined locations, but in practice, the technology has a random element. Aim it at one spot in a genome and you'll change it in one of several possible ways. Unplanned changes, or "off targets," can appear far away in the genome, too.

In plants, this randomness isn't such a problem. A successful genetic change to a single seed (an "event," as plant engineers call it) can be multiplied into a million more fairly quickly. In pigs, it's necessary to create identical edits in many animals in order to establish a population of founder pigs for breeding.

In experiments on pig cells, the Genus researchers have tried many possible edits to the *CD163* gene, looking for those that occur most predictably. Even with such efforts, the pigs being born have the right edit only about 20 to 30% of the time. Those piglets whose genomes have errors end up in a compost heap. "I want to convey that this technology is not simple. You can be good at this technology or bad at it," says Mark Cigan, a molecular biologist with a senior role in the program. "We need to be rigorous, because we want a predictable change in all the pigs. It has to be the same change every time."



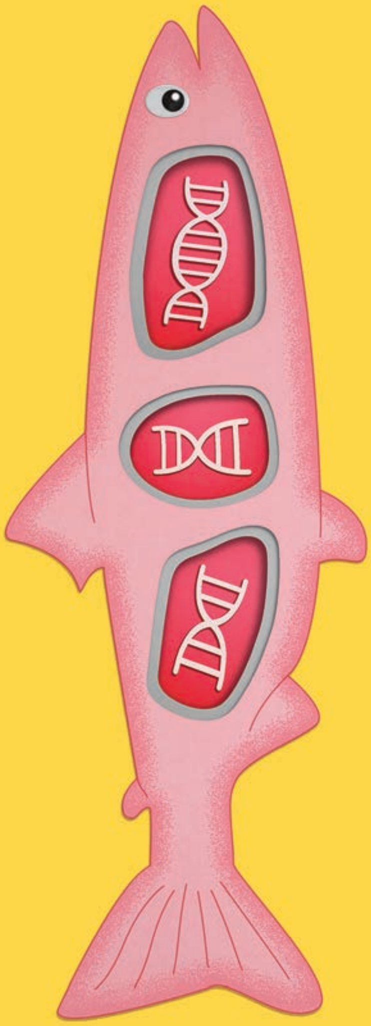
Eradicating influenza

While PRRS is the big problem in the US, Genus and other companies think they can make pigs immune to other viruses too. They are exploring whether gene editing could create pigs that don't catch African swine fever, a disease that's rampant in China and since 2018 has led to the loss of half that country's pigs. Researchers like Rowland say edited pigs could also have the indirect benefit of lowering the chance that certain viruses will spill over from pigs to humans.

The origins of covid-19 are still undetermined, but the prevailing theory is that the disease is zoonotic, meaning it jumped from animals to people. Since pigs don't catch the new coronavirus, they probably played no part in covid-19's emergence. But pig farms are notorious for starting flu pandemics. Pigs can catch both bird and human influenza, in addition to swine flu. That makes them a dangerous mixing vessel in which flu viruses can swap stretches of DNA with each other.

Such a reassortment of genetic parts can suddenly produce a new flu virus that spreads among people, who will not have immunity. The 2009 H1N1 swine flu carried viral elements from birds, pigs, and humans. In the US there were about 61 million cases: almost 300,000 people ended up in the hospital, and around

WHAT'S ON THE MENU: FAST-GROWING SALMON AND SLOW-SWIMMING TUNA



In the nursery rhyme, the first little piggy goes to market. But what if it has had its genome altered with CRISPR? Then it's a lot more complicated.

In the US a number of genetically modified animals have been approved or cleared for sale. There's the neon GloFish with added fluorescence, which you can find at a pet store. And there are a handful of goats, rabbits, and chickens engineered to manufacture drugs in their milk or eggs.

But so far, only one genetically engineered animal has been approved in the US as food. That animal, an Atlantic salmon engineered to grow faster on fish farms, took 20 years to win a nod from regulators, and then got held up for four more years over a labeling dispute. Its maker, AquaBounty, predicted late last fall that it would be ready to sell salmon to distributors in the US by December.

Aquabounty's long (and expensive) trip to the marketplace has been discouraging. Who wants their product to be denounced as a frankenfish by environmental campaigners or be prominently labeled as "bioengineered"? Yet now that the fish has won approval, it may be a "wildly important" signal to others working on genetically engineered animals, says Jack Bobo, a former board member at the company. "All GMO research on animals basically stopped for 20 years," he says. "There was no reason to do it until something got approved."

The Aquabounty salmon is transgenic—it has a gene from a different species (a Chinook salmon) pasted in. Now, though, with new gene-editing tools, researchers have better ways to introduce gene changes and a wider menu of possible enhancements. Already, gene editing has led to experimental pigs that resist viral infections and dairy cattle whose spots have been changed from black to gray, to thrive in hot climates.

Animal behavior is on the table too. In 2019, Japanese researchers tried changing a gene in tuna fish to slow them down. Tuna can swim at 40 miles per hour (about seven times as fast as Michael Phelps) and often die in sushi fish farms after collisions with walls.

The path to your dinner table remains a difficult one for these innovations. Activists will criticize them as enabling intensive livestock farming, and it's true that many genetic innovations were devised to solve problems created by crowding animals together, like disease.

And the US agency that oversees genetically modified food animals, the Food and Drug Administration, is no pushover. The FDA considers alterations to an animal's genome to be just like a veterinary drug. That means it wants evidence that the modifications do what their makers say and that they're safe, for the animals and for us.

Ultimately, though, it will be consumers and food marketers who decide how gene editing fares in the fish and meat aisles. Will people buy salmon or pork chops slapped with labels saying they are genetically engineered? The arrival of the Aquabounty salmon to the market could help answer the question. The company is angry about being required to use such labels and says its fish are just as good as anyone's. Still, as Bobo says, "it's best to be transparent and hope that people don't really care."

IF GENE EDITING IS PERFECTED IN PIGS— A SPECIES ANATOMICALLY SIMILAR TO HUMANS— WHAT WILL BE THE IMPLICATIONS FOR PEOPLE?

12,500 died. The deadly 1918 flu pandemic was accompanied in the US by a "hog flu," though the connection between them remains unproven.

Starting last year, Genus has been paying a Kansas State University scientist, Jürgen Richt, to help design pigs resistant to influenza. Richt isn't sure he can render pigs entirely immune to the fast-evolving flu viruses, but he's hopeful he can slow the pathogens down, maybe even enough to lower the odds of another pandemic. "If you get less replication, you get less mutation, less reassortment," he says. The end result is less evolution of the virus.

Because the receptors influenza attaches to are so common in the body, no animal could survive their removal, Richt says. So the project aims instead to remove other genes, for proteins called proteases that the flu—and covid-19—require as helper molecules to effectively enter cells. Because there are many types of flu, it will be necessary to remove more than one protease, leading to the question of whether pigs with too many deleted genes can thrive. If a pig is a Jenga tower, just how many blocks can be removed before the animal falls apart?

"I don't know the limit to taking out genes. That is why we do trial and error," says Richt. "But what we want is to make them resistant to all influenzas, from all walks of life."

It's not clear yet whether the PRRS-resistant pigs, with only one receptor removed, are healthy and otherwise normal. Cigan says the company thinks they are; researchers can't see other differences in their tests, which measure things like how much the pigs eat and gain weight. But unplanned changes could be subtle.

Richt says a decade ago he was involved in making cattle resistant to mad cow disease. After removing one gene, he sensed they were changed. "The way they stood up was funny—it was hard to get them back up," he says. "The caretaker told me they are stupid, so maybe intelligence was affected." With only a dozen cows, he never was sure, but he suspects the cattle lost a "luxury function"—one that wasn't vital to survival but whose removal led to a degradation of the sensory system.

Black Plague

If gene editing is perfected in pigs—a species anatomically so similar to humans that doctors hope to transplant pig kidneys to humans someday—what will be the implications for people? The debate about human genetic modification has often been reduced to asking whether it would be moral to change a child's eye color or intelligence, for instance. But the pig hatchery shows that CRISPR might be able to give people inborn "genetic vaccines" against the worst infectious diseases they might encounter.

The scientists in China who edited human embryos to resist HIV were pursuing just such a revolutionary development. And the problems they ran into were similar to those Genus faces: they couldn't control the exact edits they made and couldn't be sure that disrupting one gene (called *CCR5*) wouldn't have unanticipated consequences. In that experiment, though, there were no second tries. In addition, many questioned whether the risky attempt was medically necessary, since drugs can keep HIV under control for decades.

Since the Chinese fiasco, the American and British science academies have said that gene editing, when it's safe enough to use in human reproduction, should avoid "enhancement" of any kind and instead take on narrower goals, such as preventing people from passing inherited conditions like sickle-cell disease to their children.

Yet others think it's important to master the technology as a possible guard against future pandemics. Removing a receptor from the next generations of humans could be civilization's fallback if society is hit with a super-disease that can't be controlled by vaccines or drugs, and for which we don't develop immunity.

"We as a species need to maintain the flexibility, in the face of future threats, to take control over our own heredity," George Daley, the dean of Harvard Medical School, told an audience in Hong Kong in 2018. He listed "resistance to global pandemics" as one reason to develop techniques to modify human beings.

Covid-19 shows how a novel germ can explode out of nowhere and spread globally. The overall death rate from an infection with the new coronavirus, perhaps 0.5%, doesn't threaten humanity's existence. But what if the next pandemic is more like the Black Plague, which killed one-third or more of the population of Europe in the Middle Ages? It's a remote possibility, like an asteroid strike. But being able to engineer humans to resist specific germs might be a back-pocket technology worth having.

From what they know of animals, scientists at Genus think editing humans is futuristic but not impossible. Twenty years ago, Rice would have said it was pure fiction. "But now we can actually do it for animals," she says. "We have the tools."

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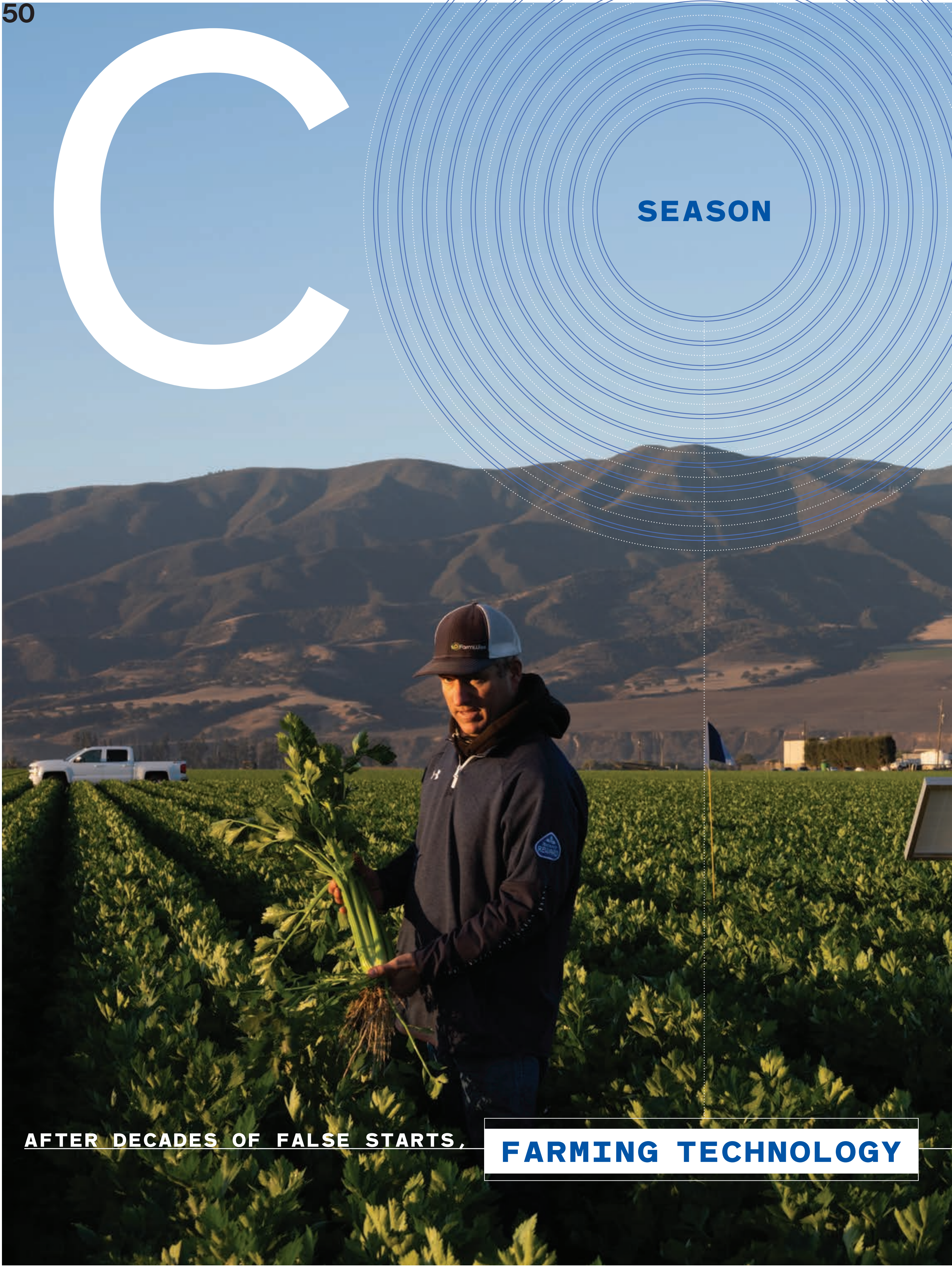


C

SEASON

AFTER DECADES OF FALSE STARTS, **FARMING TECHNOLOGY**

DE

APPROACHES AN INFLECTION POINT.

By **ROWAN MOORE GERETY**

Photographs **by Lucas Foglia**

Mark Mason is a manager with Steinbeck Country Produce, which uses a flux tower to measure how much water is evaporating from plants' leaves.

I

As a machine operator for the robotics startup FarmWise, Diego Alcántar spends each day walking behind a hulking robot that resembles a driverless Zamboni, helping it learn to do the work of a 30-person weeding crew.

On a Tuesday morning in September, I met Alcántar in a gigantic cauliflower field in the hills outside Santa Maria, at the southern end of the vast checkerboard of vegetable farms that line California's central coast, running from Oxnard north to Salinas and Watsonville. Cooled by coastal mists rolling off the Pacific, the Salinas valley is sometimes called America's Salad Bowl. Together with two adjacent counties to the south, the area around Salinas produces the vast majority of lettuce grown in the US during the summer months, along with most of the cauliflower, celery, and broccoli, and a good share of the berries.

It was the kind of Goldilocks weather that the central coast is known for—warm but not hot, dry but not parched, with a gentle breeze gliding in from the coast. Nearby, a harvest crew in straw hats and long sleeves was making quick work of an inconceivable quantity of iceberg lettuce, stacking boxes 10 high on the backs of tractor-trailers lining a dirt road.

In another three months, the same scene would unfold in the cauliflower field where Alcántar now stood, surrounded by tens of thousands of two- and three-leaf seedlings. First, though, it had to be weeded.

The robot straddled a planted bed three rows wide with its wheels in adjacent furrows. Alcántar followed a few paces back, holding an iPad with touch-screen controls like a joystick's. Under the hood, the robot's cameras flashed constantly. Bursts of air, like the pistons in a whack-a-mole arcade game, guided sets of L-shaped blades in precise, short strokes between the cauliflower seedlings, scraping the soil to uproot tiny weeds and then parting every 12 inches so that only the cauliflower remained, unscathed.

Periodically, Alcántar stopped the machine and kneeled in the furrow, bending to examine a "kill"—spots where the robot's array of cameras and blades had gone ever so slightly out of alignment and uprooted the seedling itself. Alcántar was averaging about an acre an hour, and only one kill out of every thousand plants. The kills often came in sets of twos and threes, marking spots where one wheel had crept out of the furrow and onto the bed itself, or where the blades had parted a fraction of a second too late.

Taking an iPhone out of his pocket, Alcántar pulled up a Slack channel called #field-de-bugging and sent a note to a colleague 150 miles away about five kills in a row, with a hypothesis about the cause (latency between camera and blade) and a time stamp so he could find the images and see what had gone wrong.

In this field, and many others like it, the ground had been prepared by a machine, the seedlings transplanted by a machine, and the pesticides and fertilizers applied by a machine. Irrigation crews still laid sprinkler pipe manually, and farmworkers would harvest this cauliflower crop when the time came, but it isn't a stretch to think that one day, no person will ever lay a hand to the ground around these seedlings.

Technology's race to disrupt one of the planet's oldest and largest occupations centers on the effort to imitate, and ultimately outdo, the extraordinary powers of two human body parts: the hand, able to use tweezers or hold a baby, catch or throw a football, cut lettuce or pluck a ripe strawberry with its calyx intact; and

AG TECH BOOSTERS HAVE BEEN PROMISING A SURGE OF GADGETS AND SOFTWARE THAT WOULD REMAKE FARMING FOR AT LEAST 15 YEARS. THEY MAY FINALLY BE ON TO SOMETHING.

the eye, which is increasingly being challenged by a potent combination of cloud computing, digital imagery, and machine learning.

The term "ag tech" was coined at a conference in Salinas almost 15 years ago; boosters have been promising a surge of gadgets and software that would remake the farming industry for at least that long. And although ag tech startups have tended to have an easier time finding investors than customers, the boosters may finally be on to something.

Silicon Valley is just over the hill from Salinas. But by the standards of the Grain Belt, the Salad Bowl is a relative backwater—worth about $10 billion a year, versus nearly $100 billion for commodity crops in the Midwest. Nobody trades lettuce futures like soybean futures; behemoths like Cargill and Conagra mostly stay away. But that's why the "specialty crop" industry seemed to me like the best place to chart the evolution of precision farming: if tech's tools can work along California's central coast, on small plots with short growing cycles, then perhaps they really are ready to stage a broader takeover.

Alcántar, who is 28, was born in Mexico and came to the US as a five-year-old in 1997, walking across the Sonoran Desert into Arizona with his uncle and his younger sister. His parents, who are from the central Mexican state of Michoacán, were busily setting up the ingredients for a new life as farmworkers in Salinas, sleeping in a relative's walk-in closet before renting a converted garage apartment. Alcántar spent the first year at home, watching TV and looking after his sister while his parents worked: there was a woman living in the main house who checked on them and kept them fed during the day, but no one who could drive them to elementary school.

In high school, Alcántar often worked as a field hand on the farm where his father had become a foreman. He cut and weeded lettuce, stacked strawberry boxes after the harvest, drove a forklift in the warehouse. But when he turned 22 and saw friends he'd grown up with getting their first jobs after college, he decided he needed a plan to move on from manual labor. He got a commercial driver's license and went to work for a robotics startup.

During this first stint, Alcántar recalls, relatives sometimes chided him for helping to accelerate a machine takeover in the fields, where stooped, sweaty work had cleared a path for his family's upward mobility. "You're taking our jobs away!" they'd say.

Five years later, Alcántar says, the conversation has shifted completely. Even FarmWise has struggled to find people willing to "walk behind the machine," he says. "People would rather work at a fast food restaurant. In-N-Out is paying $17.50 an hour."

Workers harvest broccoli as part of a joint project between NASA and the University of California.

II

Even up close, all kinds of things can foul the "vision" of the computers that power automated systems like the ones FarmWise uses. It's hard for a computer to tell, for instance, whether a contiguous splotch of green lettuce leaves represents a single healthy seedling or a "double," where two seeds germinated next to one another and will therefore stunt each other's growth. Agricultural fields are bright, hot, and dusty: hardly ideal conditions for keeping computers running smoothly. A wheel gets stuck in the mud and temporarily upends the algorithm's sense of distance: the left tires have now spun a quarter-turn more than the right tires.

Other ways of digital seeing have their own challenges. For satellites, there's cloud cover to contend with; for drones and planes, wind and vibration from the engines that keep them aloft. For all three, image-recognition software must take into account the shifting appearance of the same fields at different times of day as the sun moves across the sky. And there's always a trade-off between resolution and price. Farmers have to pay for drones, planes, or any field machinery. Satellite imagery, which has historically been produced, paid for, and shared freely by public space agencies, has been limited to infrequent images with coarse resolution.

NASA launched the first satellite for agricultural imagery, known as Landsat, in 1972. Clouds and slow download speeds conspired to limit coverage of most of the world's farmland to a handful of images a year of any given site, with pixels from 30 to 120 meters per side.

A half-dozen more iterations of Landsat followed through the 1980s and '90s, but it was only in 1999, with the Moderate Resolution Imaging Spectroradiometer, or MODIS, that a satellite could send farmers daily observations over most of the world's land surface, albeit with a 250-meter pixel. As cameras and computing have improved side by side over the past 20 years, a parade of tech companies have become convinced there's money to be made in providing insights derived from satellite and aircraft imagery, says Andy French, an expert in water conservation at the USDA's Arid-Land Agricultural Research Center in Arizona. "They haven't been successful," he says. But as the frequency and resolution of satellite images both continue to increase, that could now change very quickly, he believes: "We've gone from Landsat going over our head every 16 days to having near-daily, one- to four-meter resolution."

In 2014, Monsanto acquired a startup called the Climate Corporation, which billed itself as a "digital farming" company, for a billion dollars. "It was a bunch of Google guys who were experts in satellite imagery, saying 'Can we make this useful to farmers?'" says Thad Simons, a longtime commodities executive who cofounded a venture capital firm called the Yield Lab. "That got everybody's attention."

In the years since, Silicon Valley has sent forth a burst of venture-funded startups whose analytic and forecasting services rely on tools that can gather and process information autonomously or at a distance: not only imagery, but also things like soil sensors and moisture probes. "Once you see the conferences making more money than people actually doing work," Simons says with a chuckle, "'you know it's a hot area."

A subset of these companies, like FarmWise, are working on something akin to hand-eye coordination, chasing the perennial goal of automating the most labor-intensive stages of fruit and vegetable farming—weeding and, above all, harvesting—against a backdrop of chronic farm labor shortages. But many others are focused exclusively on giving farmers better information.

One way to understand farming is as a never-ending hedge against the uncertainties that affect the bottom line: weather, disease, the optimal dose and timing of fertilizer, pesticides, and irrigation, and huge fluctuations in price. Each one of these factors drives thousands of incremental decisions over the course of a season—decisions based on long years of trial and error, intuition, and hard-won expertise. So the tech question on farmers' lips everywhere, as Andy French told me, is: "What are you telling us that we didn't already know?"

III

Josh Ruiz, the vice president of ag operations for Church Brothers, which grows greens for the food service industry, manages more than a thousand separate blocks of farmland covering more than 20,000 acres. Affable, heavy-set, and easy to talk to, Ruiz is known across the industry as an early adopter who's not afraid to experiment with new technology. Over the last few years, he has become a regular stop on the circuit that brings curious tech executives in Teslas down from San Francisco and Mountain View to stand in a lettuce field and ask questions about the farming business. "Trimble, Bosch, Amazon, Microsoft, Google—you name it, they're all calling me," Ruiz says. "You can get my attention real fast if you solve a problem for me, but what happens nine times out of 10 is the tech companies come to me and they solve a problem that wasn't a problem."

What everyone wants, in a word, is foresight. For more than a generation, the federal government has sheltered growers of corn, wheat, soybeans, and other commodities from the financial impact of pests and bad weather by offering subsidies to offset the cost of crop insurance and, in times of bountiful harvests, setting an artificial "floor" price at which the government steps in as a buyer of last resort. Fruits and vegetables do not enjoy the same protection: they account for less than 1% of the $25 billion the federal government spends on farm subsidies. As a result, the vegetable market is subject to wild variations based on weather and other only vaguely predictable factors.

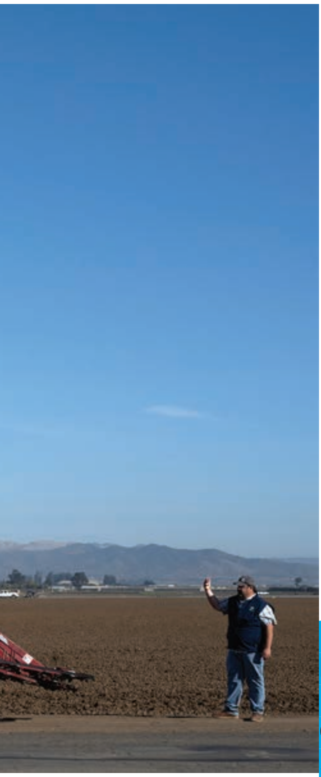
When I visited Salinas, in September, the lettuce industry was in the midst of a banner week price-wise,

Josh Ruiz, the vice president of ag operations at Church Brothers, a greens-growing concern, with "Big Red," an automated broccoli harvester of his design.

with whole heads of iceberg and romaine earning shippers as much as $30 a box, or roughly $30,000 an acre. "Right now, you have the chance to lose a fortune and make it back," Ruiz said as we stood at the edge of a field. The swings can be dramatic: a few weeks earlier, he explained, iceberg was selling for a fraction of that amount—$5 a box, about half what it costs to produce and harvest.

In the next field over, rows of young iceberg lettuce seedlings were ribbed with streaks of tawny brown—the mark of the impatiens necrotic spot virus, or INSV, which has been wreaking havoc on Salinas lettuce since the mid-aughts. These were the early signs. Come back after a couple more weeks, Ruiz said, and half the plants will be dead: it won't be worthwhile to harvest at all. As it was, that outcome would represent a $5,000 loss, based on the costs of land, plowing, planting, and inputs. If they decided to weed and harvest, that loss could easily double. Ruiz said he wouldn't have known he was wasting $5,000 if he hadn't decided to take me on a drive that day. Multiply that across more than 20,000 acres. Assuming a firm could reliably deliver that kind of advance knowledge about INSV, how much would it be worth to him?

One firm trying to find out is an imagery and analytics startup called GeoVisual Analytics, based in Colorado, which is working to refine algorithms that can project likely yields a few weeks ahead of time. It's a hard thing to model well. A head of lettuce typically sees more than half its growth in the last three weeks before harvest; if it stays in the field just a couple of days longer, it could be too tough or spindly to sell. Any model the company builds has to account for factors like that and more. A ball of iceberg watered at the wrong time swells to a loose bouquet. Supermarket carrots are starved of water to make them longer.



"WHAT HAPPENS NINE TIMES OUT OF 10 IS THE TECH COMPANIES COME TO ME AND THEY SOLVE A PROBLEM THAT WASN'T A PROBLEM."

When GeoVisual first got to Salinas, in 2017, "we came in promising the future, and then we didn't deliver," says Charles McGregor, its 27-year-old general manager. Ruiz, less charitably, calls their first season an "epic fail." But he gives McGregor credit for sticking around. "They listened and they fixed it," he says. He's just not sure what he's willing to pay for it.

As it stands, the way field men arrive at yield forecasts is decidedly analog. Some count out heads of lettuce pace by pace and then extrapolate by measuring their boots. Others use a 30-foot section of sprinkler pipe. There's no way methods like these can match the scale of what a drone or an airplane might capture, but the results have the virtue of a format growers can easily process, and they're usually off by no more than 25 to 50 boxes an acre, or about 3% to 5%. They're also part of a farming operation's baseline expenses: if the same employee spots a broken irrigation valve or an empty fertilizer tank and makes sure the weeding crew starts on time, then asking him to deliver a decent harvest forecast isn't necessarily an extra cost. By contrast, the pricing of tech-driven forecasts tends to be uneven. Tech salespeople lowball the cost of service in order to get new customers and then, eventually, have to figure out how to make money on what they sell.

"At 10 bucks an acre, I'll tell [GeoVisual] to fly the whole thing, but at $50 an acre, I have to worry about it," Ruiz told me. "If it costs me a hundred thousand dollars a year for two years, and then I have that aha! moment, am I gonna get my two hundred thousand dollars back?"

IV

All digital sensing for agriculture is a form of measurement by proxy: a way to translate slices of the electromagnetic spectrum into understanding of biological processes that affect plants. Thermal infrared reflectance correlates with land surface temperature, which correlates with soil moisture and, therefore, the amount of water available to plants' roots. Measuring reflected waves of green, red, and near-infrared light is one way to estimate canopy cover, which helps researchers track evapotranspiration—that is, how much water evaporates through a plant's leaves, a process with clear links to plant health.

Improving these chains of extrapolation is a call and response between data generated by new generations of sensors and the software models that help us understand them. Before the launch of the EU's first Sentinel satellite in 2014, for instance, researchers had some understanding of what synthetic aperture radar, which builds high-resolution images by simulating large antennas, could reveal about plant biomass, but they lacked enough real-world data to validate their models. In the American West, there's abundant imagery to track the movement of water over irrigated fields, but no crop model sufficiently advanced to reliably help farmers decide when to "order" irrigation water from the Colorado River, which is usually done days ahead of time.

As with any Big Data frontier, part of what's driving the explosion of interest in ag tech is simply the availability of unprecedented quantities of data. For the first time, technology can deliver snapshots of every individual broccoli crown on a 1,000-acre parcel and show which fields are most likely to see incursions from the deer and wild boars that live in the hills above the Salinas Valley.

The problem is that turning such a firehose of *1*s and *0*s into any kind of useful insight—producing, say, a text alert about the top five fields with signs of drought stress—requires a more sophisticated understanding of the farming business than many startups seem to have. As Paul Fleming, a longtime farming consultant in Salinas, put it, "We only want to know about the things that didn't go the way they're supposed to."

And that's just the beginning. Retail shippers get paid for each head of cauliflower or bundle of kale they produce; processors, who sell pre-cut broccoli crowns or bags of salad mix, are typically paid by weight. Contract farmers, hired to grow a crop for someone else for a per-acre fee, might never learn whether a given harvest was a "good" or a "bad" one, representing a profit or a loss for the shipper that hired them. It's often in a shipper's interest to keep individual farmers in the dark about where they stand relative to their nearby competitors.

In Salinas, the challenge of making big data relevant to farm managers is also about consolidating the universe of information farms already collect—or, perhaps, don't. Aaron Magenheim, who grew up in his family's irrigation business and now runs a consultancy focused on farm technology, says the particulars of irrigation, fertilizer, crop rotations, or any number of variables that can influence harvest tend to get lost in the hubbub of the season, if they're ever captured at all. "Everyone thinks farmers know how they grow, but the reality is they're pulling it out of the air. They don't track that down to the lot level," he told me, using an industry term for an individual tract of farmland. As many as 40 or 50 lots might share the same well and fertilizer tank, with no precise way of accounting for the details. "When you're applying fertilizer, the reality is it's a guy opening a valve on a tank and running it for 10 minutes, and saying, 'Well that looks okay.' Did Juan block number 6 or number 2 because of a broken pipe? Did they write it down?" Magenheim says. "No! Because they have too many things to do."

Then there are the maps. Compared with corn and soybean operations, where the same crops get planted year after year, or vineyards and orchards, where plantings may not change for more than a generation, growers of specialty crops deal with a never-ending jigsaw puzzle of romaine following celery following broccoli, with plantings that change size and shape according to the market, and cycles as short as 30 days from seed to harvest.

For many companies in Salinas, the man standing astride the gap between what happens in the field and the record-keeping needs of a modern farming business is a 50-year-old technology consultant named Paul Mariottini. Mariottini—who planned to become a general contractor until he got a computer at age 18 and, as he puts it, "immediately stopped sleeping"—runs a one-man operation out of his home in Hollister, with a flip phone and a suite of bespoke templates and plug-ins he writes for Microsoft Access and Excel. When I asked the growers I met how they handled this part of the business, the reply, to a person, was: "Oh, we use Paul."

Mariottini's clients include some of the largest produce companies in the world, but only one uses tablets so that field supervisors can record the acreage and variety of each planting, the type and date of fertilizer and pesticide applications, and other basic facts about the work they supervise while it's taking place. The rest take notes on paper, or enter the information from memory at the end of the day.

When I asked Mariottini whether anyone used software to link paper maps to the spreadsheets showing what got planted where, he chuckled and said, "I've been doing this for 20 years trying to make that happen." He once programmed a PalmPilot; he calls one of his plug-ins "Close-Enough GPS." "The tech industry would probably laugh at it, but the thing that the tech industry doesn't understand is the people you're working with," he said.

"EVERYONE THINKS FARMERS KNOW HOW THEY GROW, BUT THE REALITY IS THEY'RE PULLING IT OUT OF THE AIR."

V

The goal of automation in farming is best understood as all encompassing. The brief weeks of harvest consume a disproportionate share of the overall budget—as much as half the cost of growing some crops. But there are also efforts to optimize and minimize labor throughout the growing cycle. Strawberries are being grown with spray-on, biodegradable weed barriers that could eliminate the need to spread plastic sheeting over every bed. Automated tractors will soon be able to plow vegetable fields to a smoother surface than a human driver could, improving germination rates. Even as analytics companies race to deliver platforms that can track the health of an individual head of lettuce from seed to supermarket and optimize the order in which fields get harvested, other startups are developing new "tapered" varieties of lettuce—similar to romaine—with a compact silhouette and leaves that rest higher off the ground, in order that they might be more easily "seen" and cut by a robot.

Overall, though, the problems with the American food system aren't about technology so much as law and politics. We've known for a long time that the herbicide Roundup is tied to increased cancer rates, yet it remains widely used. We've known for more than 100 years that the West is short on water, yet we continue to grow alfalfa in the desert, and use increasingly sophisticated drilling techniques in a kind of water arms race. These are not problems caused by a lack of technology.

Michael Cahn, a researcher at the University of California who's developing software to optimize water and fertilizer use, at a water trial for artichokes.

On my last day in Salinas, I met a grower named Mark Mason just off Highway 101, which cuts the valley in two, and followed him to a nine-acre block of celery featuring a tidy tower of meteorological equipment in the center. The equipment is owned by NASA, part of a joint project with the University of California's Agriculture and Natural Resources cooperative extension office, or UCANR.

Eight years ago, amid news of droughts and forest fires across the West, Mason felt a gnawing sense that he ought to be a more careful steward of the groundwater he uses to irrigate, even if the economics suggested otherwise. That led him to contact Michael Cahn, a researcher at UCANR.

Historically, water in Salinas has always been cheap and abundant: the downside of under-irrigating, or of using too little fertilizer, has always been far larger than the potential savings. "Growers want to sell product; efficient use is secondary. They won't cut it close and risk quality," Cahn said. The risk might even extend to losing a crop.

Of late, though, nitrate contamination of drinking water, caused by heavy fertilizer use and linked to thyroid disease and some types of cancer, has become a major political issue in Salinas. The local water quality control board is currently developing a new standard that will limit the amount of nitrogen fertilizer growers can apply to their fields, and it's expected to be finalized in 2021. As Cahn explained, "You can't control nitrogen without controlling your irrigation water." In the meantime, Mason and a handful of other growers are working with UCANR on a software platform called Crop Manage, designed to ingest weather and soil data and deliver customized recommendations on irrigation and fertilizer use for each crop.

Cahn says he expects technological advances in water management to follow a course similar to the one being set by the threat of tighter regulations on nitrogen fertilizer. In both cases, the business argument for a fix and the technology required to get there lie somewhere downstream of politics. Outrage over lack of access to clean groundwater brought forth a new regulatory mechanism, which unlocked the funding to figure out how to measure it, and which will, in turn, inform the management approaches farmers use.

In the end, then, it's political pressure that has created the conditions for science and technology to advance. For now, venture capital and federal research grants continue to provide an artificial boost for ag tech while its potential buyers—such as lettuce growers—continue to treat it with a degree of caution.

But just as new regulations can reshape the cost-benefit analysis around nitrogen or water use from one day to the next, so too can a product that brings clear returns on investment. All the growers I spoke to spend precious time keeping tabs on the startup world: taking phone calls, buying and testing tech-powered services on a sliver of their farms, making suggestions on how to target analytics or tweak a farm-facing app. Why? To have a say in how the future unfolds, or at least to get close enough to see it coming. One day soon, someone will make a lot of money following a computer's advice about how high to price lettuce, or when to spray for a novel pest, or which fields to harvest and which ones to abandon. When that happens, these farmers want to be the first to know.

Rowan Moore Gerety, the author of Go Tell the Crocodiles, is a writer in Phoenix, Arizona.

ONE MAN'S CRUSADE TO ELIMINATE A GLOBAL SCOURGE WITH THE MOST COMMON INGREDIENT IN THE KITCHEN.

IRON MAN

BY ANNA LOUIE SUSSMAN ARTWORK BY NATALIE ANDREW

WHEN HE WAS GROWING UP, Venkatesh Mannar and his siblings treated the family saltworks as their playground: they would slide down mountains of salt drying in the sun the way other children might sled down snow-covered hillsides.

The salt operation, in the southern Indian port city of Thoothukudi, had been founded by his grandfather's grandfather. As they had for generations, men stood in the brine, using wooden trowels to rake thick crusts of salt that formed on shallow pools of seawater, and then piled it high to dry into crystals.

After several years in the United States, first studying and then working at salt producers that used giant mechanized harvesters, Mannar returned to India in 1972, intent on building a large, modern saltworks facility near Chennai with the mechanical know-how he'd gained. Then, in the early 1980s, the world began to take an interest in eliminating iodine deficiency, which causes problems ranging from hypothyroidism to learning difficulties. Mannar, while continuing to run his business, became a consultant for UNICEF and the World Health Organization (WHO). He visited countries in Asia, Africa, and Latin America to persuade them to iodize their salt, a practice that has been common in much of the developed world for decades.

He recalls arriving once in the Democratic Republic of the Congo and discovering that the WHO representatives there couldn't even tell him where salt was being produced: "They had no information!" Mannar took a car to a local market and strolled around, polling the shopkeepers selling salt on where they got it. After reconstructing the supply chain that way, he tracked down the country's salt producers to talk to them about iodine. Mannar figures he went to over 50 countries on similar missions. Today, an estimated 6 billion people globally have access to iodized salt, in no small part thanks to Mannar.

But from the early days, Mannar was also concerned with another element that many people don't get enough of: iron. A lack of it is one cause of anemia, which affects over 1.6 billion people. The condition is especially prevalent in South Asia and sub-Saharan Africa. In India alone, more than half of reproductive-age women are anemic, along with nearly 60% of children under five. Its symptoms include dizziness, poor maternal and infant health, decreased cognitive function, and the telltale listlessness that Indians call "lack of blood."

About the artwork: Natalie Andrew is a visual artist and a biologist whose work explores the boundaries separating art and science, allowing each to inspire the other. For the sculptures *Land and Sea I and II*, she filled ceramic pots with salt water from Boston Harbor and captured the crystal structures that formed over time.

Mannar thought salt, which is consumed nearly universally and with almost every meal, might be the best vehicle to deliver small amounts of iron that would have a huge public health impact. "Even from the 1970s I was very conscious about iron deficiency," he says. "It became a secondary priority because of the push with iodine."

Mannar eventually made defeating anemia with iron-enriched salt part of his life's mission. Adding iron to salt that is already iodized—resulting in so-called double-fortified salt—has turned out to be a technical challenge orders of magnitude harder than iodization. Getting manufacturers and the public to adopt it is another problem again. But if the effort succeeds, Mannar and his backers hope to add yet more essential minerals, turning humble table salt into one of the most potent public health tools the world has at its disposal.

IF you ever sat at the breakfast table as a child and wondered how your morning bowl of cereal could boast that it provided so much of the recommended daily allowances of science-class-sounding things like thiamine, niacin, and riboflavin, then you have experienced the wonders of micronutrient fortification, or supplementing commonly eaten foods with trace minerals and vitamins.

Micronutrient fortification can be designed for specific populations (as with fortified breakfast cereals, cacao-based drinks for kids, or fortified infant formula), or for everyone. Iodized salt, milk fortified with vitamins A and D, and enriched flour are a few examples.

The idea that a lack of certain trace elements causes common afflictions was established by nutritionists starting in the 19th century. A shortage of iodine was tied to goiter—an inflammation of the thyroid gland, which needs iodine to synthesize key hormones—and to "cretinism," an archaic name for developmental delays and cognitive impairments. A lack of zinc leads to diarrheal disease in children. Other ailments caused by nutrient deficiencies were also identified, and specific foods were prescribed as cures: lemons for scurvy, cod liver oil for rickets, meat and milk for beriberi. (In one of the earliest documented instances of fortification, in 1873, French bakers included cod liver oil in bread destined for hospitalized children.)

In 1906, Frederick Gowland Hopkins of Cambridge University challenged his colleagues to learn more about what he called "unsuspected dietetic factors" in an organism's health. His first paper on "accessory factors" was published in 1912; it would take several decades for scientists to come to an understanding of the chemical structures of what we now call vitamins.

Meanwhile, during the First World War, US Army officials noticed a pattern among young men called up for the draft. Goiter, identifiable by the prominent swelling of the thyroid in the front of the neck, was more common among men from the center of the country, and less so among draftees from the coasts. One medical history of salt iodization records that "according to US Selective Service regulations, more men were disqualified for military service in Northern Michigan for large and toxic goiters than for any other medical disorder"; surveillance studies ultimately found a prevalence above 64% in some parts of the state.

Why did their coastal peers fare better? Seawater contains iodine, some of which evaporates into the air and then returns to earth in rain. Coastal soil, therefore, is far richer in iodine than soil inland, and plants grown near the coasts have higher iodine levels. Seaweed and seafood, which are more common in coastal diets, also contain enough iodine to make a nutritional difference.

Authorities in three French provinces had begun distributing iodine tablets as early as the 1860s. In 1922, landlocked Switzerland became the first country to systematically iodize salt. By 1924, the Morton salt company, based in Chicago, began selling iodized salt across the United States, and eventually 90% of American households came to use it.

Not until 1990 did the UN World Summit for Children set the goal of eliminating iodine deficiency disorders worldwide, but the effort has been a resounding success: the number of countries classified as iodine deficient fell from 110 in 1990 to 25 by 2015. Meanwhile, fortifying milk with vitamin D has led to the near eradication of rickets, and enriching flour with niacin and other minerals eliminated pellagra, a condition marked by diarrhea, dermatitis, and dementia that killed as many as 7,000 Americans annually at its peak in the late 1920s but was virtually nonexistent by 1950.

The striking exception to this litany of successes is anemia. Though the disease has many causes, including parasitic infections and other nutrient deficiencies, the most common is a lack of iron, which is responsible for about half of worldwide anemia cases. Anemia results in weakness and reduced cognition. For pregnant women it can, along with folic acid deficiency, increase the odds of birth defects like anencephaly, which is usually fatal.

Economists believe high rates of iron-deficiency anemia also have a macroeconomic effect, reducing individual productivity by as much as 40% and reducing GDP by over 1%. According to the Copenhagen Consensus Center, which does cost-benefit analyses of large-scale social interventions, salt iodization costs around five cents per person per year, and one dollar spent on it generates as much as $30 in saved health-care costs and higher economic productivity. Iron fortification, it's estimated, would generate almost $9 for each dollar spent—not as dramatic as iodization, but still a substantial impact.

Part of the reason anemia is so prevalent in India is that almost 200 million Indians live in extreme poverty, and many rarely or never eat meat, either for religious reasons or because it is simply unaffordable. Grains and pulses, the staples of most Indian diets, are rich in phytates, compounds that inhibit the absorption of iron, exacerbating the problem. Anemia was common even in Mannar's relatively well-off social circle. Though more severe in India than elsewhere, it isn't a problem confined to the poor world. Some 3.5 million people are diagnosed with anemia each year in the United States, according to the Centers for Disease Control, and over 5,000 die from it annually.

But, as Mannar notes, richer people can visit a doctor and buy iron supplements, while poorer Indians, especially in rural areas, likely can't. Government interventions in India, such as a program to give pregnant women iron tablets, had also made little sustained impact. Distributing pills to hundreds of millions of people and persuading them to take them regularly was hard. Iodized salt, however, was already in shops and kitchens, and used in every meal. Why not, Mannar thought, just add iron to it as well?

The idea had been around since 1969. But as Mannar and competing groups in India and Switzerland (among others) would discover, both the chemistry of iron and the complexities of nutrition made things considerably harder.

Iodizing salt is a relatively simple matter: a solution containing 2% to 4% potassium iodate is dripped or sprayed on salt that has already been dried and refined. Alternatively, the potassium iodate can be mixed with a filler, sprinkled over dry salt, and mixed again.

Adding iron to iodized salt—making double-fortified salt, or DFS—turns out to be an entirely different class of problem.

When iron comes into contact with potassium iodate, they react. The iodine evaporates, and the iron forms compounds that are less easily absorbed by the body. The salt darkens and takes on a metallic taste—hardly something someone would want to sprinkle on food.

Mannar learned all of this the hard way. In 1993, he walked into the office of Levente Diosady, a professor of food engineering at the University of Toronto who specialized in processing edible oilseeds, and told him about the idea for DFS. "He said, 'This should be pretty easy—can we do a couple of tests?'" Diosady recalls. "I said, 'Yeah, we can do a couple of tests, but it probably won't be that easy.'" The two received a small grant from a recently created group called the Micronutrient Initiative to explore the technical side of creating DFS.

"They said, 'Well, you know, we've been spending the last 10 years telling people that salt should be white and clear and clean with nothing in it. And here you are doing this, and it looks like there's mouse droppings in it.'"

Diosady knew the key was to keep the iron and iodine from coming into contact with one another, but he didn't have a clear idea of how to do it. He and one of his lab technicians tried to create iodine microcapsules with a thin, water-resistant coating around each particle, to form a barrier between the iodine and the iron. They tried several encapsulant formulas, but they found that to mix evenly with salt, the spray-dried microcapsules had to be ground up very fine. In a test in Ghana, consumers complained that the results were clumpy.

"At that point, we went back and said, Okay, well, what can we do to make it bigger? So we started looking at agglomerating these iodine particles to make them more or less match salt in size," says Diosady. "That was the goal: to make stuff that matches salt grains in size to prevent separation."

In the early years of the project, salt in most countries was neither as uniform nor as sparkling white as it is today, which worked to Diosady's advantage. "Color was not a big deal. Particle size was not a big deal. It was variable," he recalls. But as production centralized, salt became more consistent in appearance and taste. "We were chasing a moving target—the quality of salt over the last 20 years has improved steadily," Diosady says.

Unable to get the iodine capsules to work the way they wanted, Diosady and his team decided to change tack and focus on encapsulating the iron instead. That way whatever they came up with could, in principle, be mixed in with existing iodized salt.

That left the question of what kind of iron to use. "We went and tried a whole slew of iron compounds," says Diosady. Most resulted in an off-color salt that would never fly with consumers. He's reminded of these failed attempts every year, when winter arrives in Toronto. "I still use salt in my driveway which is yellow, green—all the different colors that these things came up with," he says.

Mannar suggested ferrous fumarate, a compound widely used in iron tablets because the body absorbs it easily. One of the cheapest forms, it also has the advantage of being flavorless—other iron compounds can taste like a rusty pipe.

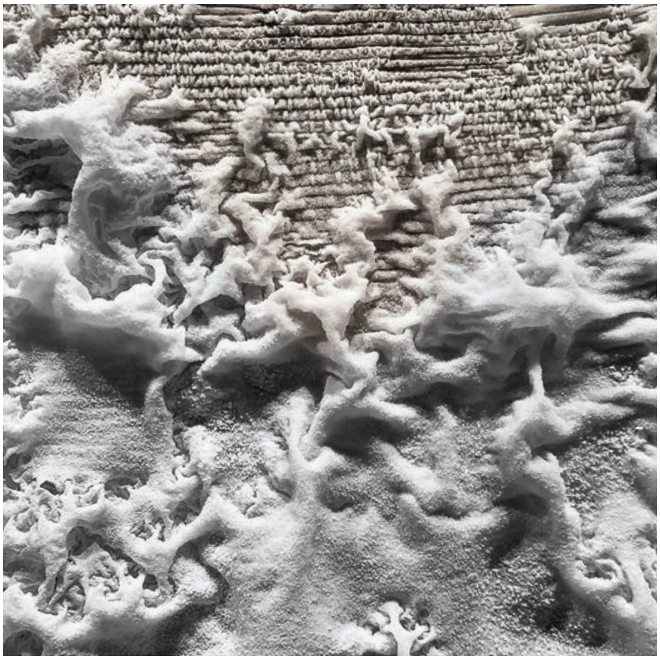
Ferrous fumarate comes in powder form. Diosady and his graduate students would suspend the powder in a precisely controlled stream of air that flows up into a cone-shaped container, while simultaneously injecting an adhesive that allows the particles to coagulate in salt-grain-size clumps. These clumps could then be sprayed with a waterproof coating, so that if they encountered any humidity they wouldn't dissolve, thereby preventing the iron within from reacting with the iodine. These little particles now formed an iron "premix" that could be added to iodized salt.

There was just one problem. Ferrous fumarate ranges in color from a cocoa brown to the bright red of paprika or cayenne. Diosady recalls bringing the iron-enriched salt to a meeting of specialists led by Mannar. "They said, 'Well, you know, we've been spending the last 10 years telling people that salt should be white and clear and clean with nothing in it. And here you are doing this, and it looks like there's mouse droppings in it.'"

To get the right color, they eventually settled on a formula based on stearin (a tasteless vegetable fat used in everything from candles to confectionery), which provides the waterproof layer, mixed with enough titanium dioxide (an inert food additive, and the same mineral that makes some sunscreens chalky) to tint the particles white.

But these techniques relied on a sophisticated piece of equipment known as a fluidized-bed agglomerator, used in pharmaceutical manufacturing. The machines can cost a couple of million dollars each. Diosady's team gradually ramped up to making the premix in 600-kilogram batches, enough for 120,000 kilograms of double-fortified salt, but there was no way developing countries would be able to afford the technology.

The team needed a cheaper, simpler method. They eventually hit upon extrusion—squeezing a "dough" made of ferrous fumarate mixed with semolina, water, and a tiny bit of shortening through a restaurant pasta machine, to create strands the diameter of angel-hair pasta. These are cut into pellets of equal length and diameter, which are then sieved to ensure evenly sized pieces of no more than 800 micrometers, or a 30th of an inch: around the size of a single grain of salt. The pellets are, as before, coated in titanium dioxide and stearin, making them resemble tiny, irregular Tic-Tacs, which can then be mixed with salt.



To understand how their product would hold up in the real world, Diosady and his team used data gathered by a kind of salt tracking device—a small metal box slightly bigger than a pack of cards that could be packaged in salt shipments bound for shops in Kenya and Nigeria. The device captured snapshots of atmospheric conditions every 30 minutes over the course of the three-month journey from factory to shop. Using this data, they set large ovens to approximate various environments—from the tropical coast of Mombasa to the hot, dry atmosphere in Kano, Nigeria, to the temperate weather of Nairobi—and left Ziploc bags full of salt in them for months, finally testing them for stability.

Satisfied they'd created an adequately fortified, shelf-stable product, the researchers next had to find out if it would actually do the job they had designed it for: overcoming iron deficiency and preventing anemia. That process has taken even longer than developing the technology itself.

AS Diosady and Mannar were getting their efforts under way, a group at India's National Institute of Nutrition in Hyderabad developed a competing double-fortified salt, as did a research group at the Swiss Federal Institute of Technology. When the Swiss salt was tested in Morocco and Côte d'Ivoire, the results were mixed. One study showed levels of iron-deficiency anemia decreasing from 35% to 8% among Moroccan schoolchildren after 40 weeks, but another concluded that the encapsulation techniques still needed work.

In 2006, with funding from the Canadian government, the Indian state of Tamil Nadu began using Diosady's salt formulation in lunches provided to 5 million schoolchildren. In 2008, a consortium of Swiss and Indian researchers began testing both Diosady's formula and an alternative Swiss compound in 18 villages near Bangalore, some 200 miles west of where Mannar had grown up, to compare how well different forms of iron worked.

Iodine tends to react with impurities in salt, causing it to evaporate, so iodized salt becomes less effective over time. The Swiss salt, which contained iron in the form of ground-up ferric pyrophosphate, lost 44% of its iodine content in the first month of storage, and 86% after six months. But Diosady's version performed just as well as regular iodized salt, losing just a fifth of its iodine content after six months. And in both kinds, the iron did its job: the Swiss formula cut the rate of anemia in the schoolchildren in half, and the Toronto version performed even better. The stearin coating, just a few microns thick, had proved to be up to the task. (Ferric pyrophosphate, used in the Swiss salt, is already white, eliminating the need for a coating, though the iron in it is less easily absorbed by the body.)

In 2014, results came back from another evaluation, conducted by research groups at Cornell and McGill universities. Diosady and Mannar's DFS was given to 212 female tea pickers on an estate in Darjeeling, a lush green region in West Bengal, in the foothills of the Himalaya mountains. Of the 93 women who had too little iron in their blood at the outset of the study, 80% had normal levels by the end, about eight months later. Even better, their cognition and memory improved. A trial at 54 schools in the Indian state of Bihar in 2018, by a group from the University of Göttingen, found that DFS reduced anemia by 20%.

All the same, at least one major study has cast some doubts on the case for adding iron to salt. In a 2017 paper, Abhijit Banerjee, Sharon Barnhardt, and Esther Duflo reported that a trial they conducted across 400 villages in Bihar found "no evidence that either selling DFS or providing it for free has an economically meaningful or statistically significant impact on hemoglobin, anemia, physical health, cognition or mental health."

That result carries some weight, since Banerjee and Duflo won the 2019 Nobel in economics for their work on evaluating the impact of development programs. In their paper, the researchers speculated that to avoid the risk of iron poisoning, the dose in the salt they were using might have been too small to overcome the iron deficiency.

Their study was one of 14 covered in a 2018 meta-analysis in the journal Advances in Nutrition, coauthored by Mannar. Overall, it found DFS effective at delivering iron and reducing anemia. More research may be needed. (Mannar says his salt tastes better than the formulation that Banerjee, Barnhardt, and Duflo studied.) But even if the benefits of iron-fortified salt aren't yet certain, a lot of investment is going into making it more widely available.

Mannar has overseen hundreds of fortification programs. He is partial to salt because it is cheap, and because rich and poor people eat similar amounts.

The president of the Micronutrient Initiative was so pleased with Diosady and Mannar's early work (and so keen to return to medical practice) that in 1994 he offered Mannar the presidency of the organization, which changed its name to Nutrition International in 2017. Mannar has overseen hundreds of fortification programs. He is partial to salt because it is cheap, and because rich and poor people eat similar amounts.

But Diosady wonders if even iodizing salt would be politically feasible today, despite its benefits, if it hadn't already been done decades ago. Educated consumers have grown wary of tinkering with food and increasingly seek out the "natural." Many tons of pink salt, which has a virginal, untouched aura, are mined in the Himalayas and exported. Diosady notes that even his own wife "is very leery of anything I bring from the lab."

By 2016, the Food Safety and Standards Authority of India had finalized regulatory language governing the production of DFS. A manufacturing plant run by JVS Foods in Jaipur, in northwestern India, began to manufacture the premix at scale, in a process based on the one designed by Diosady and his team: JVS bought a few pieces of equipment and manufactured the rest, including extruders and coating machines. Mannar and researchers from the University of Toronto then persuaded salt processors to incorporate the premix. The plant's initial output of 600 tons of premix a year was enough to supply over 40 million people. Diosady estimates that India now has capacity to produce DFS for 100 million people per year.

The state government of Uttar Pradesh, in India's north, was the first to scale up distribution, beginning in late 2016. The salt was rolled out to 25 million consumers there through a network of 15,000 "fair price shops," which sell government-subsidized staples. Other states followed: Madhya Pradesh in 2017 and Jharkhand in 2018. In September of that year, Prime Minister Narendra Modi plugged the salt in his weekly address to the nation.

Diosady estimates that it took $35 million, invested over 20 years, to develop the microencapsulation technology, test it in the field, and provide technical assistance to JVS to jump-start production. Funding came from various sources, including the Micronutrient Initiative, the Canadian government, the Bill and Melinda Gates Foundation, and the Tata Trusts, one of India's largest philanthropies. Ratan Tata, the industrialist who heads the trusts, is a fortified-salt enthusiast, as is Bill Gates.

Still, whether DFS follows the path first trodden by iodized salt, from targeted intervention to universal condiment, depends in large part on whether commercial saltmakers can be enticed to begin manufacturing it at scale. That, argues Rajan Sankar, a program director for nutrition at the Tata Trusts and a former advisor to the Micronutrient Initiative, requires government intervention. India's iodization push of the 1980s and 1990s succeeded because the government helped saltmakers buy modern equipment and provided free potassium iodate and technical support. If the public health authorities are serious about combating anemia, he asks, "What is the support [they] are ready to give?"

Mannar's nephews now own and operate the family saltworks—he sold his own share decades ago. In the summer drying season, the flats still teem with laborers harvesting salt manually, but there is now a large, airy plant where salt is washed, ground, and iodized in huge metal vats. Sacks of salt, stacked a dozen high, await dispatch. But despite Mannar's encouragement, the business doesn't yet sell a double-fortified salt. "They would like to," he says. But they are waiting for the market leaders to make the first move.

Anna Louie Sussman is working on a book about the relationship between capitalism and reproduction.

"HE PUT QR-CODED WRISTBANDS ON EACH OF THE CHICKENS"

TR: Q + A

One author argues that China's rural agriculture doesn't just feed that nation—it powers the future.

By Samantha Culp

Blockchain Chicken Farm, a new book from Oakland-based writer, designer, and scholar Xiaowei Wang, explores technology in rural China and the surprising ripple effects of the country's food supply chain on people all around the world. The book connects, for example, an AI-driven pig-farming operation in Guangdong to Silicon Valley surveillance culture, while avoiding the easy binaries of tech solutionism and paranoia. It also includes a selection of speculative "Sinofuturist recipes," an ongoing art project that uses food to address anxieties about technology, the ecosystem, and the body. We discussed Wang's research, the effects of the coronavirus pandemic, and what China's food system means for us all.

Q: Your book is a travelogue that weaves in experimental recipes, family history, and the surrealist details that link a Zhejiang pearl farm with multilevel marketing schemes in the American South. How did you capture such a complex narrative?

A: So much tech reporting focuses on technological "solutions" in a way that too often becomes a form of marketing, and I really didn't want to do that. It was important for me to examine the underlying social fabric of these issues surrounding food—so, everything from food safety to this idea of hunger and food scarcity, especially in a place like China, where that is actually in recent memory.

Q: What are the fundamental differences between rural populations in China and the US today?

A: In the US, most of our farmers are people doing industrial agriculture. But in China, there's still a huge population doing smallholder farms, and physically working the land. Obviously, that's changing, but I wanted to understand how this pretty traditional scene was meeting high tech. I think people don't realize how there are just so many people in China and also not as much land as in the US, so the Chinese agricultural system faces unique pressures. A lot of elderly folks in China lived under the Great Leap Forward, which was this time of enormous starvation throughout China because Mao Zedong was trying not

CHRISTIE HEMM KLOK

A: I was frustrated because much media coverage of the ASF outbreak focused on how Alibaba was doing this heroic thing to save all these pigs and guarantee food safety using AI to monitor the herds via video, temperature, and sound sensors. In fact, for decades now, there's been a push to industrialize hog farming in China, and these technologies were an attempt to produce even more pigs at an unprecedented scale. These industrial farms and increased pressure for output set up the conditions for epidemics like swine fever in the first place. What are the paradoxes it reveals?

only to collectivize agriculture, but to have the agricultural yields surpass those of the West—to prove that "China can do it too." So there's the history of these really tightly controlled agricultural policies, as well as rations on food purchases, that continues into the early 1980s. For many older Chinese, the idea of going into a supermarket and buying whatever you want is still kind of incredible.

Q: You discuss the "New Socialist Countryside" policy. What is it, and how did it lay the groundwork for some of the innovations you describe?
A: It's a rural revitalization policy that the national government embarked on a few years ago to encourage innovation in the countryside. It's an attempt to balance a lot of what the government views as shaky forces. A lot of farmers want to move to cities because they see economic opportunities there, but then city folks are anxious about a high number of migrants, and migrants don't receive the same benefits, like health care, when they're in cities, due to China's *hukou* ["residential permit"] system.

So how do you keep people in the countryside but at the same time give them economic opportunities, especially because farming is not an easy job, and increasingly the younger generation doesn't want to be stuck doing manual labor in the field? The national government is entranced with some of the same shiny keywords as policymakers everywhere—"e-commerce" "blockchain," "AI"—so it's supported a lot of initiatives by small privatized companies that employ those technologies.

Q: One of these inspired your book's title. Can you explain what makes a "blockchain chicken farm"?
A: It's a small farm in rural Guizhou where the farmer had been raising free-range chickens for quite a long time, but he couldn't convince people that they were actually free-range. Then a Shanghai tech company came along and said, "Blockchain is the solution!" They worked with the farmer and he put QR-coded wristbands on each of the chickens, so that they could be surveilled by cameras to prove that they were truly free-range and never tampered with.

Q: You also cover AI machine-learning models like Alibaba's "ET Agricultural Brain," which became a tool for combating African swine fever (ASF) in pigs during a disastrous outbreak that began in 2018.

Q: What's an example of a farming technology that is taking a different path?
A: Like many countries, China is a place where the government tried to modernize agriculture by using pesticides and fertilizers as the "scientific" way of farming the land. In one rice-farming village in Guangdong province, farmers did that and over time noticed that their soil was just not as fertile anymore, that they had to keep using more and more fertilizer. This led to the Rice Harmony Collective, which revived traditional techniques like "rice duck fish" agriculture, where fish and ducks in the rice paddy act as a natural pesticide. They also introduced a lottery system for rice paddy location that shifts each season, so that farmers have a greater incentive to follow these organic rules.

CHRISTIE HEMM KLOK

Q: The coronavirus pandemic emerged when your book was in production. Do you feel it underscores your themes?
A: I had been looking at a lot of the research of Rob Wallace, an epidemiologist who studies factory farming and zoonotic diseases—which is not to say that all these are coming out of factory farms, but just these profit-driven practices that push humans into previously wild habitats. There's obviously been a huge acceleration of zoonotic disease.

In the pandemic we've all realized that decoupling with China would be hard—we rely on China for so many things. Just the process of setting up a factory; the material supplies, training, machinery; the knowledge of costs and shipping and freight and routes. It's never been more clear that China is so interwoven with the global supply chain.

Q: What do you wish Americans understood about Chinese wet markets?
A: So, I love wet markets. They are a place where fresh food is readily available to all, and it's an important livelihood for many people who aren't these large supermarket chains. You've got the garlic lady who sells her homegrown crop at wet markets. They're a crucial connection for local and regional farmers. They're so common not just in China, but around the world—in Latin America and so on. I think it's sad [that people blame covid-19 on wet markets]—and a xenophobic example of people thinking that Chinese food is somehow "dirty." It infuriates me so much, because all the science says it [the coronavirus] probably came from outside [the market], and it probably came from a bat.

Q: What are the trends you are seeing in the countryside? Has the pandemic contributed to new ones?
A: I would say the general trend is that there's lots of optimism. Because of the pandemic, a lot of migrant workers in cities had to go back to their rural homes, and maybe they'll stay there and pursue other kinds of opportunities. Even before the pandemic, I observed a lot of young people thinking and talking about "Oh, maybe I can move back to my hometown" and start some kind of business that would be cheaper than in the city.

I think, too, the live-streaming economy is a weird microcosm of this—people have a notion of farming in the countryside, live-streaming it, and getting patrons. I think for urban youth, that trend is increasing. Back in 2009, when I was living in Beijing and trying to do urban gardening, no one was interested. Everybody was like, "Ugh, this is what my parents had to do. I'm not doing this, it's gross." But today, there's a huge demand for organic farmers' markets, and influencers getting into farming. I just heard about a popular beekeeping influencer, who has a whole brand and blog talking about the ancient art of beekeeping. It makes sense: the urban 20-somethings who have only known the city their entire lives, they're under so much pressure, and so of course they're going to romanticize the countryside.

Q: The term "Sinofuturism" refers to concepts and aesthetics of a "Chinese future." It's been explored by artists, designers, and thinkers in critical or celebratory ways. How do you personally interpret it?
A: For me, Sinofuturism now contains a certain imperial logic, given how China has operated more and more as an imperial power over the past few years, domestically and internationally. That said, I think there are a lot of interesting and productive parts of Sinofuturism that make us question these innate Western beliefs about the value of individualism, the role of work, the disconnection from natural cycles, the separation between mind and body, that are worth investigating. Sinofuturism is also a way to consider what exactly is this imperial force that China's becoming, and to provoke questions around that.

Q: Even if they don't cook them, what do you want readers to get from the Sinofuturist recipes in the book?
A: I'd love for people to say, "Hmm, I don't have access to moon-grown cornmeal," but to have a sense of wonder about the ingredients that *are* available to them, and to frame that reality as a weird form of fiction. To question "Why do we eat what we eat?" and understand how that relates to technological change. I was really inspired by a cookbook by Mary Sia, who talks about how in China you don't get a lot of baked goods; you get a lot of boiled things, and that's due to the fact that China simply didn't have enough trees to cut down to generate as much heat as is needed in baking. For me that was a reminder of how what we cook is totally shaped by what is available, as a result of the technology that we use.

Q: What were some of the inspirations behind the recipes you include in the book?
A: I was seeing my Chinese herbalist, who loves to rant about Western medicine and how it doesn't fully understand the body, and she was telling me about how the brain is not one of the 11 vital organs in Chinese medicine. It's not essential to the system of *qi*. I thought it was fascinating because when I was interviewing computational neuroscientists, you know, the brain is the center of everything in Western clinical medicine. It controls your heartbeat, your lungs; it's the center of thinking: you wouldn't be a person without it.

My herbalist gave me some ideas on what nourishes *qi*, so I decided to use her sage advice in a recipe for AI porridge.

Samantha Culp is a writer and filmmaker based in Los Angeles.

IT'S THE KITCHEN OF THE FUTURE! AND IT ALWAYS WILL BE.

Kitchen gadgets routinely promise a better way to cook. Once in a while, they even deliver, says the editor in chief of Cook's Illustrated magazine.

By Dan Souza

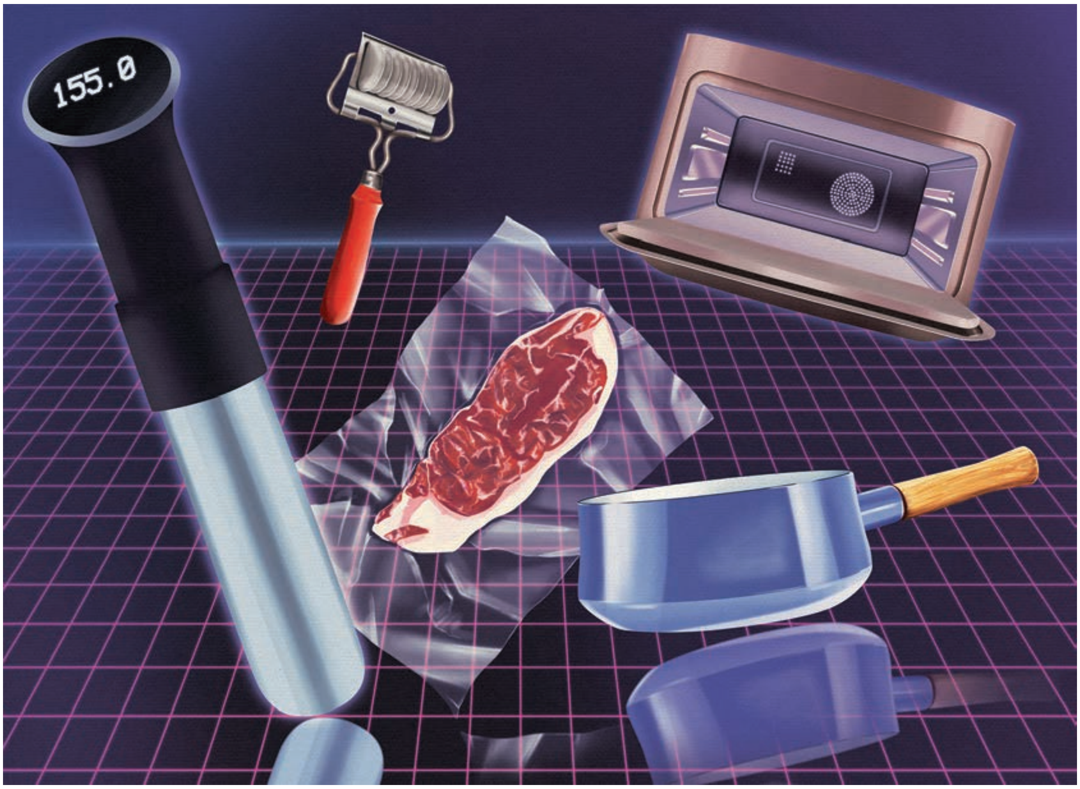
There's a long-running column in Cook's Illustrated called "What is it?" where we track down the origins of kitchen gadgets that our readers find in their attics or on dusty antique-store shelves. A recent favorite: the Acme Rotary Mincer, vintage 1935, a handheld device featuring 10 stainless-steel rotary blades, which promised to mince herbs and vegetables with "lightning rapidity." (Spoiler: it didn't.)

This section of the magazine is essentially an obituary column for kitchen technology. And we never seem to run out of tools to pay tribute to. It makes sense: for as long as humans have toiled over dinner, we've worked nearly as hard at finding ways to make that cooking easier, faster, safer, better. Many of the forgotten gadgets that end up in the column were in fact perfectly good at the task they were designed for, but what we've asked of our home kitchen technology—and what ultimately ends up in our homes—has changed over time.

In the second half of the 20th century, the poster child of kitchen innovation was the microwave oven. Borrowing tech designed for use in radar in World War II, it offered a truly novel way to cook food. A magnetron creates an electromagnetic field that reverses polarity billions of times a second, showering food with waves that cause its water and fat molecules to constantly reorient themselves. That vibration heats neighboring molecules, resulting in speedy cooking … sort of. Since microwaves can't penetrate very far into food, and the waves don't contact the food evenly, only certain parts heat quickly. Anyone who's zapped a slab of frozen lasagna and taken alternating bites of magma-hot cheese and ice-cold meat sauce knows this all too well. The microwave is fast, convenient, and imprecise.

In her 2005 New York Times Magazine story "Under Pressure," Amanda Hesser posited that sous vide—at the time a technique used almost exclusively by top and experimental chefs—would "probably trickle down to the home kitchen someday." How right she was. Today you can buy an affordable sous vide circulator, the shape and size of a Maglite flashlight, that can hold a container of water at a temperature accurate to a tenth of a degree. Let a ribeye steak, sealed in a plastic bag, swim in a 130 °F bath and it'll emerge medium-rare from edge to edge. Sous vide trades on qualities nearly antithetical to the microwave: it is slow (an hour and a half to two hours for that perfectly cooked ribeye), relatively inconvenient (you need to plan ahead and often finish the job with a final sear), and highly precise. The fact that sous vide found a real following suggests that for many home cooks today, precision is at least as important as convenience.

Do cooks in 2021 really have to make that binary choice? A clutch of sleek tech-forward appliances would have us believe the answer is no. Many promise precision on par with sous vide cooking, but with more robust capabilities—such as the ability to brown food—while providing convenience



JULIA DUFOSSÉ

through copious smart features like apps and pre-programmed recipes. Like their predecessors, a number of them rely on impressive-sounding technology to do the cooking.

Take the Brava Oven, which cooks using visible and infrared light. According to the manufacturers, inside the toaster-oven-size, windowless box are "six high powered lamps that get hotter than a wood fire pizza oven." But brute-force heat isn't the intention here. Instead, the oven targets those lights in different areas of the oven, such as the underside of the tray your food sits on, or at the food directly, to concurrently cook two different foods—say, a steak and some asparagus—on the same tray and produce an ideal version of each.

Cooking with light certainly has a futuristic sheen to it, but solid-state, or RF, cooking may be more interesting. Michael Wolf, who publishes The Spoon, a website that reports on trends in food technology, describes solid-state cooking as "taking the high-precision radio frequency technology from your phone and essentially putting it in a microwave." Comparisons to the microwave are apt in that both technologies use electromagnetic radiation with wavelengths longer than infrared light. But whereas a microwave's magnetron emits just one frequency, a solid-state module can vary the frequency and amplitude of radio waves it emits, which makes for far more even heat distribution. These waves also provide feedback to the oven, allowing it to sense colder and hotter regions and direct energy where it is needed. RF technology is starting to show up; it features in Miele's Dialogue oven, among others.

IT'S EASY TO BE WOWED BY BRIGHT LIGHTS AND THE PROMISE OF EFFORTLESS BEEF JERKY.

One of the most exciting cooking appliance technologies isn't new at all—or sexy. It's steam: or more specifically, the ability to control humidity within a convection oven. Professional cooks know that the key to precise cooking has to do with the relationship between heat and humidity, and having relied on combi (combination) ovens for decades, they know what is possible when these devices hand them fine control over both. A combi oven can mimic sous vide one minute, dehydrate beef jerky the next, and handle tasks as disparate as proofing bread and roasting meats. Home wall combi ovens are available from many big-brand appliance manufacturers, but it's the countertop models, like the new app-connected Anova Precision Oven, that just might bring combination cooking to the masses.

It's of course easy to be wowed by bright lights and the promise of effortless beef jerky. Whether any one of these appliances succeeds will have a lot to do with the "smart" side of the equation—things like app usability and how well the pre-programmed recipes turn out—as well as with price. Still, with so many options converging at the intersection of precision and convenience, some could very well find a permanent home in many of our kitchens. And for the ones that don't? We'll be more than happy to write the obit.

Dan Souza is the editor in chief of *Cook's Illustrated* magazine.

IN AN AGE OF ABUNDANCE,

WHY DO PEOPLE STARVE?

Our wonderful global supply chain is not just failing to prevent hunger—it's causing it.

By BOBBIE JOHNSON
Illustration by Nico Ortega

Nobel Prizes are rarely awarded without controversy. The prestige usually hatches a viperous nest of critics who deride the credentials of the winner, complain about the unmentioned collaborators who'll be sidelined by history, or point to the more deserving recipients who've been unfairly snubbed.

So when the Norwegian committee decided to award the 2020 Nobel Peace Prize to the World Food Program, the United Nations' food assistance agency, it was no surprise that the news was greeted with more than a few smirks and eye-rolls.

In this case, the committee said, the prize was given because "in the face of the pandemic, the World Food Program has demonstrated an impressive ability to intensify its efforts." Who could argue with that?

Plenty of people, it turns out. When UN bodies win the peace prize, "we are right at the edge of giving it to 'the idea of org charts,'" quipped the Atlantic's Robinson Meyer. "It's a bizarre choice, and it's a complete waste of the prize," said Mukesh Kapila, a professor of global health at the University of Manchester. They have a point. The WFP, which provides food assistance to people in need, is the largest agency in the UN and has 14,500 employees worldwide. It won the prize for simply doing its job, argued Kapila.

And an extremely narrow interpretation of its job, at that. After all, the UN didn't create the WFP to tackle immediate threats during an acute time of stress; its mission is to "eradicate hunger and malnutrition." After nearly 60 years of trying to end hunger, the WFP is larger and busier today than ever before. The world's farmers produce more than enough to feed the world, and yet people still starve. Why?

Hunger around the globe is getting worse, not better. It's true that the proportion of people who regularly fail to get enough calories to live has been declining, dropping from 15% in 2000 to 8.6% in 2014. Nevertheless, that proportion has since held fairly steady, and the absolute number of undernourished people has been rising. Last year, according to the UN, 688 million people went hungry on a regular basis, up from 628.9 million in 2014. The curve is not sharp, but if current trends continue, more than 840 million people may be undernourished by 2030.

The statistics seem abstract, but each one of these millions is an actual mouth to feed, and the hardships they undergo are very real. In his 2019 book *Food or War*, the Australian journalist and author Julian Cribb describes the physical process of starvation in excruciating detail. The body, he explains, devours itself in the hunt for sustenance, depleting energy levels and producing side effects like anemia, fluid build-up, and chronic diarrhea. Then "the muscles begin to waste," he writes. "The victim becomes increasingly weak."

> EVEN IN INDUSTRIALIZED COUNTRIES, THE THREAT OF HUNGER HAS BEEN RISING.

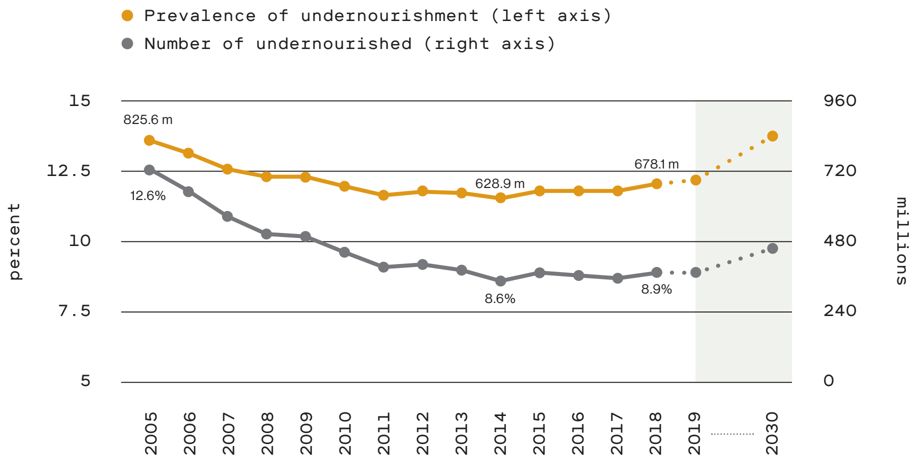
"In adults, total starvation brings death within eight to twelve weeks ... in children, prolonged starvation retards growth and mental development in ways from which they may never recover, even if sound nutrition is restored. In short, starvation is one of the most agonizing ways to die, both physically and mentally—far worse, indeed, than most tortures invented by cruel people, because it takes so long and involves the destruction of virtually every system in the human body."

Today, the global antipoverty nonprofit Oxfam identifies 10 "extreme hunger hot spots" worldwide where millions of people face this abominable torture. Some are theaters of conflict—including Afghanistan, home to the longest war America has been involved in, and Yemen, where a civil war fueled by neighboring Saudi Arabia has left 80% of the country's 24 million citizens in need of humanitarian assistance. But there are other circumstances that can bring starvation too: Venezuela's cratering economy; South Africa's high unemployment rates; Brazil's years of austerity.

And even in high-functioning industrialized countries, the threat of hunger—not just poor nutrition, but actual hunger—has been rising as a result of economic inequality. In the UK, the use of food banks has more than doubled since 2013. In the US, food insecurity is widespread, and the hardest hit are children, elders, and the poor. In Mississippi, the country's hungriest state, one

HUNGER IS INCREASING

If current trends continue, more than 840 million people may be undernourished by 2030.



SOURCE: FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

child in four is unable to consistently get enough to eat. What's happening?

It's hard to comprehend, in part because the food system has been one of the greatest technological success stories of the modern world. What we eat, how it is produced, and where it comes from—all have changed dramatically in the industrial age. We have found a way to apply almost every kind of technology to food, from mechanization and computerization to biochemistry and genetic modification. These technological leaps have dramatically increased productivity and made food more reliably and widely available to billions of people.

Farming itself has become many times more efficient and more productive. In the early 1900s, the Haber-Bosch process was harnessed to capture nitrogen from the air and turn it into fertilizer at an unprecedented scale. Mechanization came quickly: in the 1930s, around one in seven farms in the US had a tractor; within 20 years, they were used by the majority of farms. This was matched by an increasing ability to redirect water supplies and tap into aquifers, helping turn some arid regions into fertile arable land. Swaths of China, Central Asia, the Middle East, and the US were transformed by huge water projects, dams, and irrigation systems. Then, in the 1960s, the American agronomist Norman Borlaug bred new strains of wheat that were more resistant to disease, ushering in the "Green Revolution" in countries like India and Brazil—a development that led Borlaug himself to win the Nobel Peace Prize in 1970.

All of this means that industrialized farmers now operate at almost superhuman levels of output compared with their predecessors. In 1920, more than 31 million Americans worked in agriculture, and the average farm was just under 150 acres. A century later, the total acreage of farmland in the US has fallen by 9%, but just one-tenth of that workforce, 3.2 million people, is employed to tend it. (There are also far fewer farms now, but they are three times larger on average.)

The supply chain, too, is a futuristic marvel. You can walk into a store in most countries and buy fresh goods from all over the world. These supply chains even proved somewhat resistant to the chaos caused by the pandemic: while covid-19 lockdowns did lead to food shortages in some places, most of the empty shelves were the ones meant to hold toilet paper and cleaning products. Food supplies were more resilient than many expected.

But the mass industrialization of food and our ability to buy it has created an avalanche of unintended consequences. Cheap, bad calories have led to an obesity crisis that disproportionately affects the poor and disadvantaged. Intensive animal farming has increased greenhouse-gas emissions, since meat has a much larger carbon footprint than beans or grains.

The environment has taken a beating, too. Booms in fertilizer and pesticide use have polluted land and waterways, and the easy availability of water has led some dry parts of the world to use up their resources.

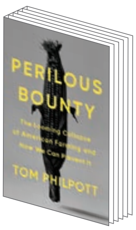
In *Perilous Bounty*, the journalist Tom Philpott explores California's agricultural future. The massive water projects drawing supplies into the Central Valley, for example, have helped it become one of the world's most productive farming regions over the past 90 years, providing around a quarter of America's food. But those natural aquifers are now under acute pressure, overused and running dry in the face of drought and climate change. Philpott, a reporter for Mother Jones, points to the nearby Imperial Valley in Southern California as an example of this folly. This "bone-dry chunk of the Sonoran desert" is responsible for producing more than half of America's winter vegetables, and yet "in terms of native aquatic resources, the Imperial Valley makes the Central Valley look like Waterworld." The valley is home to California's largest lake, the 15-mile-long Salton Sea—famously so loaded

SIX OF THE BEST

A selection of recent books that shed light on the perils of the food system.

Food or War
Julian Cribb
CAMBRIDGE UNIVERSITY PRESS, 2019
–
A rapid-fire tour of the impending conflicts created by the food system—and the ones that are already playing out.

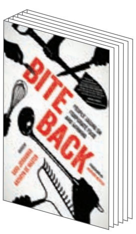
Uncertain Harvest
Ian Mosby, Sarah Rotz, Evan D.G. Fraser
UNIVERSITY OF REGINA PRESS, 2020
–
Can we adapt our diets to handle impending catastrophe? Take a tour through the foodstuffs that might dominate our future, from caribou to crickets.



Perilous Bounty
Tom Philpott
BLOOMSBURY, 2020
–
How the intensification of farming in America has left industrial agriculture looking shaky and facing collapse.

Feeding the People
Rebecca Earle
CAMBRIDGE UNIVERSITY PRESS, 2020
–
Potatoes are totally familiar, entirely unglamorous, and utterly vital to the global diet. Earle details the potato's surprisingly fascinating social and political history.

Harvesting Prosperity
Keith Fuglie, Madhur Gautam, Aparajita Goyal, and William F. Maloney
WORLD BANK GROUP, 2020
–
This free, wonky e-book contains a detailed exploration of the remaining potential for farming and a blueprint for progress.



Bite Back: People Taking on Corporate Food and Winning
edited by Saru Jayaraman and Katherine De Master
UNIVERSITY OF CALIFORNIA PRESS, 2020
–
This essay collection examines a number of angles on attaining food justice.

with pollutants and salt that nearly everything in it has been killed off.

This isn't going to get better anytime soon: what is happening in California is happening elsewhere. Cribb shows in *Food or War* exactly how the trend lines are pointing the wrong way. Today, he says, food production is already competing for water with urban and industrial uses. More people are moving to urban areas, accelerating the trend. If this continues, he says, the proportion of the world's fresh water supply available for growing food will drop from 70% to 40%. "This in turn would reduce world food production by as much as one-third by the 2050s—when there will be over 9 billion mouths to feed—instead of increasing it by 60% to meet their demand."

These are all bleak predictions of future hunger, but they don't really explain starvation today. For that, we can look at a different unexpected aspect of the 20th-century farming revolution: the fact that it didn't happen everywhere.

Just as healthy calories are hard to come by for those who are poor, the industrialization of farming is unevenly distributed. First Western farmers were catapulted into hyper-productivity, then the nations touched by the Green Revolution. But progress stopped there. Today, a hectare of farmland in sub-Saharan Africa produces just 1.2 metric tons of grain each year; in the US and Europe the equivalent land yields up to eight metric tons. This is not because farmers in poorer regions lack the natural resources, necessarily (West Africa has long been a producer of cotton), but because they are locked into a cycle of subsistence. They haven't industrialized, so they don't grow much food, which means they can't make much money, so they can't invest in equipment, which means they can't grow much food. The cycle continues.

COURTESY OF THE PUBLISHERS

This problem is exacerbated in places where the population is growing faster than the amount of food (nine of the world's 10 fastest-growing countries are in sub-Saharan Africa). And it can be increased by sudden poverty, economic collapse, or conflict, as in Oxfam's hot spots. While these are the places where the World Food Program steps in to alleviate immediate pain, it also doesn't solve the problem. But then, their economic plight is not an accident.

In September 2003, a South Korean farmer named Lee Kyung Hae attended protests against the World Trade Organization, which was meeting in Mexico. Lee was a former union leader whose own experimental farm had been foreclosed in the late 1990s. In an essay in the collection *Bite Back* (2020), Raj Patel and Maywa Montenegro de Wit recount what happened next.

As demonstrators clashed with police, they explain, Lee climbed the barricades with a sign reading "WTO! Kills. FARMERS" hanging around his neck. On top of the fence, "he flipped open a rusty Swiss Army knife, stabbed himself in the heart, and died minutes later."

Lee was protesting the effects of free trade, which has been a disaster for many farmers worldwide. The reason farmers in less industrialized nations can't make much money isn't just that they have low crop yields. It's also that their markets are flooded with cheaper competition from overseas.

Take sugar. After the Second World War, Europe's sugar-beet growers were subsidized by their national governments to help ravaged countries get back on their feet. That worked, but once industrialization kicked in and production levels reached the stratosphere, they had an excess. The answer was to export that food, but the subsidies had the effect of artificially lowering prices: British sugar farmers could sell their goods in global markets and undercut the competition. This was good news for Europeans, but terrible news for sugar producers like Zambia. Farmers were locked into subsistence, or decided to turn away from the foods that they were naturally able to produce in favor of other products.

Powerful nations continue to subsidize their farmers and distort global markets even as the WTO has forced weaker countries to drop protections. In 2020, the US spent $37 billion on such subsidies, a number that has ballooned under the last two years of the Trump administration. Europe, meanwhile, spends $65 billion each year.

Patel and Montenegro point out that much of the populist political chaos of recent years has been a result of the trade turmoil—industrial jobs lost to outsourcing, and rural protests in the US and Europe by people angry at the prospect of rebalancing a deck that has been stacked in their favor for decades.

Donald Trump, they write, "was never honest about ditching free trade," but "the social power he stirred up in the Heartland was real. Invoking the abominations of outsourced jobs, rural depression, and lost wages, he tapped in to neoliberal dysfunction and hitched the outrage to authoritarian rule."

All this leaves us with a bleak picture of what's next. We have built systems that don't just widen the gap between rich and poor but make the distance unassailable. Climate change, competition for resources, and urbanization will produce more conflict. And economic inequality, both at home and abroad, means the numbers of hungry people are more likely to rise than fall.

THIS IS HARD TO DO, BUT CLIMATE CHANGE MAY FORCE US TO DO IT REGARDLESS.

So are there any answers? Can starvation ever be ended? Can we head off the approaching food and water wars?

The countless books about the food system over the past few years make it clear: solutions are easy to lay out and extraordinarily complicated to enact.

First steps might include helping farmers in poor countries out of the trap they are in by enabling them to grow more food and sell it at competitive prices. Such a strategy would mean not only providing the tools to modernize—such as better equipment, seed, or stock—but also reducing the tariffs and subsidies that make their hard work so unsustainable (the WTO has attempted to make progress on this front). The World Food Program, for all its plaudits, needs to be part of that kind of answer—not just an org chart plugging hungry mouths with emergency rations, but a force that helps rebalance this off-kilter system.

And food itself needs to be more environmentally sound, employing fewer tricks that increase yields at the expense of the wider ecology. No more farming oases set up in bone-dry deserts; no more Salton Seas. This is difficult, but climate change may force us to do some of it regardless.

All of this means recognizing that the golden age of farming wasn't a golden age for everybody, and that our future may look different from what we have become used to. If so, that future might be better for those who go hungry today, and maybe for the planet as a whole. It may be hard to reckon with, but our spectacular global food system isn't what will stop people from starving—it's exactly why they starve in the first place.

Bobbie Johnson is a commissioning editor at MIT Technology Review.


BY ANJALI SACHDEVA
ILLUSTRATIONS BY JOAN WONG

Fiction

Dark spaces on the map

"To portray meaningful relationships for a complex, three-dimensional world on a flat sheet of paper or a video screen, a map must distort reality ... [A] single map is but one of an indefinitely large number of maps that might be produced for the same situation or from the same data ..."

—Mark Monmonier, *How to Lie with Maps*

In the future, the young tell your memories back to you, and you listen. If you try to tell them about a sunny day in spring when you were 15 they immediately look it up and say *no, it was raining that day, not sunny. Remember?* After a while you learn to be quiet and let them tell it. You can say, "What was my birthday like?" They type it in, and within seconds they have a report: *When you were six your mother invited your two best friends for a little party in the kitchen. There was* sabzi *and* roti *and raspberry cake. You got a doll. Here is a picture of you holding it; here is a video of you opening the box*. They are not conscious of the things they can't see, or why those things matter. You remember that doll's dress as green instead of blue, because when you were that age your mother had a green dress with the same kind of lace collar as the doll's. She loved that dress and wore it often, and consequently you loved it as well. *No, no, the doll's dress was blue*, they will tell you, and they are right, but they can't feel what you feel, that little echo of your mother's dress, that little echo of your love for your mother, attached to your doll. The way you carried that doll everywhere until it was gray, and the dress was rags—that, they can tell you about, but they never really understand why.

It's the same when they look back at men, which they do all the time, endlessly fascinated: *men in the wild!* They can watch your father hold you on his lap; they can even catch a whiff of his roast-beef-and-cigarettes smell, though they have never seen a real cigarette and the smell confuses them. But they can't feel him, the incredible tenderness and patience of the way he taught you to make a proper cup of tea or drive a car, the strength of his body and the exhaustion of it after a long day of work. They say *he seems like a good father*, but to them it's all academic. How many minutes per day he spent with you. How many books he read to you. How many decibels his voice rose when he was angry. None of the important stuff.

There is so much information. Photographs, videos, receipts, social media posts, medical records, school transcripts, search histories. Quizzes to find out which character you most resemble from television shows that ended decades before any of them were born. Conversations stealthily recorded by smart speakers or electronic toys. And that's before you add in the information that has nothing to do with you in particular: air quality reports, news articles, traffic camera footage, the Billboard Hot 100. All of it accumulated, filed, cross-referenced, interwoven. And when they're really desperate, when there are too many holes in the data, they go for recovered memories, though the difficulty and expense means they have to justify the need. But they justify as much as they can. They love to see how it all matches up, how your reported memories fit the data streams fit the neural harvest—or don't. So often they don't, and it's always your brain that's lacking, that's incorrect.

The girl who comes to talk with you is bright. Observant. Fatima is her name. You know she'd hate being called a "girl," but at your age almost everyone seems like a child. You never had children, but now you've got her.

You don't entirely agree with the project she's working on. It smacks too much of self-satisfaction: a fact-finding mission to prop up the status quo, to prove in a brand-new, scientifically advanced way that men were intolerable, though of course the investigators tell themselves they are unbiased. But that same project brings her back to talk to you, again and again. Though you know Fatima thinks of you primarily as a case study, it's no small thing to spend months sharing your life with someone, especially someone who listens as carefully as she does.

When the two of you talk she smooths her headscarf back over her hair, presses her lips together for a brief moment, and then launches into an endless string of inquiries. She rarely dwells on the present for any longer than it takes to say *how are you today?* because what she really wants to know about is your past. She's taken that whole "living history" thing very much to heart. You want to tell her that history dies as well as lives, that parts of it fade away every day, through the deaths of its makers, through forgetfulness and intentional obsolescence. That she can gather data like wildflowers, fill her skirts, and it will not change the fragility of history.

Today she asks about Uncle Paxton, your father's brother. About a time you and your mother and siblings went swimming with him at the public pool. Your father was supposed to come too, but he'd had to stop at the office first and had gotten stuck behind a traffic accident leaving downtown.

"Yes," says Fatima. "An overturned semi transporting chickens. I saw the news footage."

"My mother was angry when he called to say he wouldn't make it."

"Did she say *why* she was angry?"

You work hard not to smile. Fatima thinks her questions are subtle, but you always know right away when she's sniffing around for something specific. She's obviously been perusing the information she's gathered about this particular day. The videos of you and your uncle, the trace of fear on your face when he stands near you. In emails and social media, the greater frequency of negatively connoted words when you wrote about him, the lack of likes and hearts on his posts. Now she's trying to gently prod you to put whatever she's assembled into context.

You shrug. You know what she's looking for. She thinks if she asks you just the right question you'll say *My uncle touched me once* or *My dad told her Paxton was a little sick in the head*. She can see, in the data, the little signs pointing that direction.

But you won't say anything negative about him, because there's nothing concrete to say. He never did anything bad to anyone, that you can verify. It wouldn't be fair to say what you do remember: That there was a chill that came off him. You looked at him and just knew there was something wrong somewhere, like a broken bone beneath unbroken skin. Your mother knew it; your father too. They never left you or your siblings alone with him. There's nothing in the record to condemn him, but there's a lot that was never said where Uncle Paxton was concerned.

"My mother bought us all ice cream," you say now. "She always said the ice cream at the pool was too expensive, but that day we all got our own and she didn't complain once."

Fatima nods, makes a note in your file. She smiles her tight little smile of longing—never enough information to sate this one—and moves on to another line of questioning.

In spite of all the hours spent talking, there are some things you don't tell Fatima about. The night that changed your life, for instance, which started out with something painfully mundane: you wanted to break up with your boyfriend. You were 22, and in six years you'd be living in a whole different world, a world without boyfriends, but of course you didn't know that then. If Fatima were to sift through your data channels leading up to that night, she'd understand that the breakup was a long time coming. January's data: two tickets for a trip to the skating rink; a cabin at a state park and an accompanying grocery bill for salmon and chocolate and six bottles of red wine; a photo of a giant cat made out of snow, wearing his gloves and your scarf. March: dinner at a perfectly nice chain restaurant; grocery store roses; a copy of a book he thought you'd like, though you didn't. June: nothing but a record of a video queue crammed with action flicks, and a case of light beer. By late August, you were done. You just hadn't told him yet.

The night was humid, hot, rich with the threat of storms, but you went out anyway. There was a huge park a few blocks from your house, built around a series of wooded ravines and gullies that flattened themselves into picnic grounds in the lower elevations, the grass full of fireflies at dusk. You left your phone at home, in part because you didn't want to risk it getting wet if it did rain, but more because you didn't want to be reachable. You didn't want your boyfriend calling you in the middle of your rumination; you didn't want to talk to your parents or siblings or even your friends. You just wanted to think. And as it turned out, you'd have plenty to think about.

Fatima is a graduate student. At first you wished you'd been assigned someone with a little more cachet. But you quickly realized the logic behind it. No one but a student could devote the amount of time to you that she does. Or the interest. Even you don't find yourself as interesting as she seems to, but you know it's not really about you at all.

When the men were sent away, their stories went with them—their poems and movies, their symphonies, their paintings. Then came a half-century where the bookstores and theaters had nothing but *l'art de la femme*, and old-timers like you swapped drives full of contraband hip-hop and novels with the corners worn off. But then, eventually, the restrictions eased. And this new generation, Fatima's generation, is savvy enough to realize that the last women who actually *remember* the Common Era are almost gone, that if she and her colleagues want to know what it was really like, separate from all the propaganda, they'd better act quickly.

Practically, this means you never know when she'll show up at your care home. It's going on 10 p.m. when you see her reflection appear behind you in the sitting-room mirror. She looks sad, lacking her usual vivacious edge. Her headscarf is rumpled. You turn and call a hello.

"Everything all right?" you ask.

She nods, says it's just stress, pressure from her senior researcher to get better results so they don't lose their grant. She sits down beside you and swipes her thumb across her communication cuff, shoots you a little taste of what she's feeling in that casual way young people do, as though it's never crossed their minds that you might not want to experience their emotions, even for a moment. Your feel a faint twinge as

They love to see how it all matches up, how your reported memories fit the data streams fit the neural harvest—or don't.

your own cuff, synched with hers, releases neurochemicals into the artery at your wrist, and a momentary wave of Fatima's anxiety and exhaustion passes through you. You look at your comm cuff with annoyance but say, "Is there anything I can do to help?"

Fatima smiles. When it comes to you, she is hampered by a mix of fondness and condescension. She finds your old-fashioned affectations sweet, but more than that she craves what you have, the information you have carried in your body for so many decades. She is grateful to you for preserving it, but she doesn't really believe you *understand* its worth in any important way. Better to give her that data, let her handle it. Well, you'd have been no better in your own youth, wouldn't have believed a 107-year-old woman had anything useful to say. Wouldn't have thought of yourself as anything other than impossibly old.

You ask her to walk with you, and she nods, gives you her hand as you rise to your feet. Once you reach the kitchen you ask her to make you a sandwich, tell her to make one for herself while she's at it, and then you sit back and wait while she pokes through cupboards, gathering bread and mayonnaise and mushroom patties, stacking and slicing it all. She hands you a plate.

"My dad used to make sandwiches for me in the middle of the night," you say. "He'd sneak downstairs to make one for himself, but I'd always find him. He said everything tastes better after midnight."

Whenever you say "dad" she silently repeats the word to herself, trying to get the feel of it in her mouth. You're not sure she even knows she does it. "Did he cook?" says Fatima. You can already imagine the bulleted lists forming in her mind: *C.E. division of domestic labor. Kinship structure. Popular recipes of the Common Era*.

"He did. He was a good cook. My mother cooked too, but she didn't really enjoy it."

She files this information away, and you can see her relax, just a little. She feels her time here has been useful, warranted.

"So, what is going on with your research?" you ask.

Fatima sighs. Her field is very new, this combination of biochemistry and cultural anthropology. Neural harvesting has come around at just the right time to make all kinds of leaps possible, filling in gaps in ways they hadn't imagined. But there are plenty who still think it's a waste of time, even heretical. Why should we care about back then? We already know how bad it was; what value can there be in asking more questions?

"The technology's developing so quickly, but we don't have the funding to keep up. We're finding that we can access things the Memory Holder doesn't remember consciously at all. Conversations from when you were a baby, that you'd never have understood at the time. Action in the background while you were engaged in something else. The quality's not great, but the amount of data is much more than we'd anticipated."

"Why would you want to do that?"

She looks up, bewildered. "Think of the possibilities! It's a whole other generation back. Information about your parents, maybe even your grandparents."

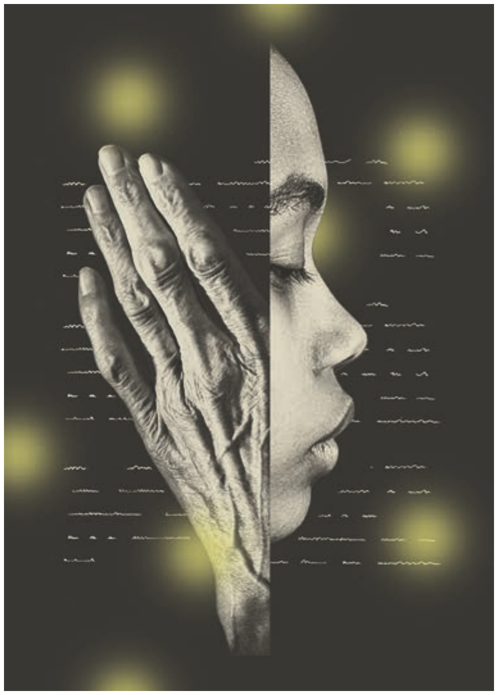
You take another bite of your sandwich. "Is that what you call me, in your reports? 'The Memory Holder'?" You picture yourself cradling your memories against your chest like soft, gray balls of yarn.

"It's what we call all the subjects."

You nod your head, thinking of them, all these other old women scattered across the country. You were 28 when the Common Era ended. An adult, to be sure, but those who spent the most time in that period, who belonged more to that world than this one, are already dead. So Fatima and the rest will work with what they've got: you, and others like you. They'll try to extrapolate and glue back together the history the previous generation so gleefully smashed. They are like archaeologists, whisking away the dust from pottery fragments with their soft little brushes. Pieces will be missing. The seams will show. But they'll have something, some museum idea of what it was like, and they'll pretend it's definitive. As if history could ever be that clear.

Those who spent the most time in that period, who belonged more to that world than this one, are already dead.

The what-ifs of that night used to haunt you. What if you'd taken your phone? What if you'd stuck to the sidewalks around your building, stayed within range of the shining blue light of technology—what then? But now you see it differently. Now that night is something they cannot wrest from you. It pleases you to have even one important memory that they don't know about. They could



neurally extract it, if they could compel you to think about it, but for the moment there's still an art to the science of memory-mining. Someday, you're certain, they'll be able to scan your entire life in the time it takes you to blink, but right now if they don't know that there's anything to extract—if they don't know what to look for—they can't find it.

Once you entered the park, you hadn't been very careful about where you were going. Your daytime familiarity with the place—picnics, sunbathing, Frisbee with your housemate and her dog—had inculcated a false sense of security. It seemed that all the trails wound down to the same soccer field eventually. And there was something enticing about the darkness, too, the depth of the shadows, occasional spears of moonlight lancing down between the leaves. You chose a trail little bigger than a deer path, followed its whims, thinking and thinking about what seemed important then, the boyfriend. You knew how to say "I think we should break up," but he was sure to ask why, and why was harder to answer, at least if you didn't want to hurt him. And you didn't. Part of it, you knew, was tied up in the whole stale life you'd built with him: packing into the same crowded bars every weekend with the same friends you'd had since your first year of college, working retail while half-heartedly applying for brand manager positions and prodding him to do the same. All of that seemed somehow much more fixable if you were single, or with someone else.

You realized, eventually, that you'd been walking for a long time, that the soccer field was nowhere in sight, that you weren't sure where you were. The forest was dense here, the trail overgrown, and you were about to reach reflexively for the phone you didn't have, to shed some light on the path, when you first heard the crying.

The sound got louder, then quieter again, before it burst into sudden clarity. A woman, not far off, her sobs underpinned by lower voices. A moment later you saw the beams of flashlights coming toward you, and without even thinking about it stepped silently off the path, into a welter of tangled bushes, and crouched to the ground. Peeking between leaves you could see a man gripping the arm of a crying woman, another man trailing close behind, complaining about the steepness of the trail. Now and then the man who held the woman's arm would tell her to shut up, or drag her forward, or say something quietly to his friend. The three of them were only 50 feet away, then 20, and then the second man swung his flashlight so that it caught the woman's face. You could see her blackening eye, her lip swollen and split clear down to the tooth, a glaze of blood on her chin dripping onto her chest. The desperation in the way she cast her eyes about, as though looking for escape. In the second that the light brushed across her face she squeezed her eyes shut against the glare, and you did too, a moment later, though the light hadn't touched you. You didn't open them again. You imagined your eyes shining in the light of the flashlight beams, giving you away. "I'm sorry, I'm sorry," the woman said, and the second man said, "Probably going to be a lot sorrier pretty soon."

I should do something, you thought, but you shrank down even further into your own body and prayed, because how could they not see you already, how could they help but see you? Except, of course, that they didn't even know to look for you. And then the crying got quieter, and the voices faded away into silence, and you finally unwound yourself. You stepped back onto the path and almost collapsed on your cramped legs, limped forward 10 feet and found that your path joined with another small trail, the one they had taken. You stood there for a moment, in a dark space on the map, thinking of the woman and her terrified eyes.

You knew the fastest way home was up, the way the men and the woman had gone, but you went downhill, turning onto one branch of the path and then another, always seeking the steepest route downward until at last you emerged from the trees, and there was the soccer field. From there you knew the way, could exit the park and go by lighted streets instead of up the main trail, the extra hour it would cost you worth every minute. You walked home on concrete, your body shuddering at every sound in the night.

When you got to your apartment, your housemate was asleep. You went straight to your room, unplugged your phone from the charger. You planned to dial 911. But what would you say? *I saw a woman and two men, none of whom I could identify, in a place I couldn't find again. I don't know where they went. It was hours ago. She was injured. No, I don't know how she got injured. No, I didn't witness any crime. She just looked scared.* You thought that if you really wanted to try to help you would have had to do it in the moment, back in the woods, when the light flashed across her face—though that, too, seemed impossible, because what could you have done? And so you put the phone back down, and brushed your teeth, and went to bed. In the morning you made a cup of coffee and called your boyfriend and said, "I think we should break up."

You sit in an armchair, pretending to play with your comm cuff while actually you are watching Fatima and her girlfriend talking outside the sliding glass doors to the home. Or perhaps "talking" is the wrong word. They say very little, mostly shooting each other bursts of emotion from their cuffs, which you can then see play across their faces. They are both flushed, angry, leaning toward tears. You think about how much it used to mean for someone to understand you, to know your feelings from the way your eyes crinkled or your smiled turned down at the corner. How the desirability of some things lies in their elusiveness.

Eventually the girlfriend leaves and Fatima comes inside to start today's interview session, wiping the sweat from her face and rubbing her eyes.

"Tough day?" you ask.

She sighs. "I think I might need to break up with my girlfriend."

It is the most personal thing she has ever shared with you, and you place a hand on her shoulder. "Maybe she just needs a little space. Have you ever tried talking without the cuffs?"

Immediately, she's retreated again, her mouth wry, her eyes clinical. "Oh, that's a thought," she says, but you hear what she means: your way of thinking about the world is outmoded. This is advice from another century, laughable in its obsolescence. The way you'd have responded if your grandmother had suggested you make up with your boyfriend by baking him a pie. How could you ever want *less* information? Surely inadequate information is the cause of all the world's ills? Well, maybe she's right. And since when are you such a fan of talking, anyway?

You never told your housemate about the woman in the woods. You didn't tell anyone. You read the local paper every day, looking for reports of missing persons, murders, assaults. It seemed that what you'd witnessed must have left a mark somewhere. But if it did, in the world outside your head, you couldn't find it.

Inside, well, that was different. You thought about her every day. But the external data is deceptive. The data shows that you ate less for the next two months. That you didn't leave the house as much as you usually did. That you listened to your music a bit louder, played the same sad songs again and again. But the data also shows, of course, that you'd just broken up with your boyfriend. If you hadn't seemed too enamored of him before the breakup, well, perhaps you'd just miscalculated your feelings. The data floats around a blacked-out space in the shape of a woman with a split mouth dripping blood.

If it happened now, of course, the comm cuff would be onto you. Even if by some miracle you were not recorded, even if no one had spoken a word through the whole encounter, Fatima would still be looking at your records and saying, "Something went wrong here. Why so much cortisol and adrenaline? Why the climb in heart rate? *Something* must have happened—tell me what." She'd hack it out of you like an unpolished diamond.

But back then no one did. You didn't offer up the information. You wanted to sit with your grief and shame. In the silence, your guilt at having done nothing grew into a determination to do *something*. You quit retail and got a job at a women's shelter, even though it meant working night shifts and giving up your weekends spent drinking in clubs. A few years later you'd be the manager, but at first you worked intake and sat at a desk at the entrance. Every day, women walked through the door who looked as though they were ready to disappear. Who did not expect anyone to care about what happened to them.

If you'd learned the name of that woman in the park, if you'd talked about her, maybe you'd have gotten over it. Maybe, when the Common Era was ending, you'd have tried harder to find a way to leave, have headed for some other country where things were going to remain more or less the same, a country full of boyfriends and brothers and fathers and men in the dark with flashlights. But you didn't. Instead, the weight of that patch of darkness shaped your life in a way light and truth never could.

Three weeks later, Fatima sits across the table from you, hunched over a mug of coffee. She has broken up with her girlfriend, but aside from this decline in posture she seems to be handling it just fine. She has been interviewing you for an hour, focusing on your time in high school, your interactions with male teachers. You're bored with the line of questioning, bored with this strange dance the two of you do. You've been thinking a lot about what you'd like to say, independent of her questions.

You interrupt her latest inquiry to ask, "Can we talk somewhere else?"

Fatima blinks. You never interrupt her. You are, for the most part, a very polite old lady.

"Is that chair not comfortable?"

"Come with me. And leave your comm here."

"What now?" she says, laughing. You fumble with the clasp on your own comm cuff, slide the cuff loose and set it on the table. You tap the space beside it.

"I'm not supposed to," she says. "I need it to record our conversation."

"I insist." You can see her doing the calculations. Hers is a face that calculates nakedly. She feels as though you've asked her to walk with her eyes closed; the request is strange but not inherently suspicious. "I want to tell you something. Something I've wanted to talk about. In private."

Her condescending side slips in. You see her relax a little. You are just guarding your secrets. You are just being a little dramatic about it. Old people and their obsession with secrecy, vestigial limb of a world where secrets still existed. She can indulge you, this once.

Old people and their secrecy, vestigial limb of a world where secrets still existed. She can indulge you, this once.

She unlocks the comm, slides it from her arm, sets it on the table with clear reluctance. The two cuffs look oddly intimate, sitting side by side.

You take her hand and lead her down the hallway. You've given a great deal of thought to where this conversation could take place. The conservatory is just off the east wing, or will be, when it's completed. For the moment it's just a big glass room filled with wicker furniture covered in drop cloths, empty stone planters, and flagstone pathways. Not a plant in sight. Or a camera. Those things will be added in a few weeks. You sit on a shrouded sofa and gesture grandly for Fatima to sit beside you. She does, trying to hide her amusement. You lean toward her.

"There's a story I've been wanting to tell you. About, you know. Back then."

She's instantly alert, the indulgent smile still on her face but barely covering her desire to know.

"I haven't told it to anyone. Not even when it happened. But I don't want it included in the literature or your official reports. It would have to be off the record."

Fatima frowns. If she agrees to this, she's ethically bound to follow through; she can't use any data, any stories, without your permission, which until now you've granted easily.

You know you're using her youth to her disadvantage here. She can see the immediate drawbacks, but you're baiting her, dangling a bit of knowledge like a lure. This girl who has devoted her life to uncovering secrets but has never had one of her own—she can't help herself. Of course she can't. Even as she promises not to tell, she assures herself that the *knowing* will be enough.

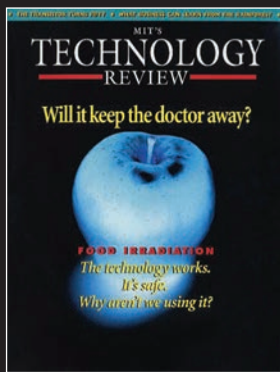
And you hope it will be. Knowing without telling, and everything that can come from it. You hope to teach her that.

Anjali Sachdeva is the author of the short story collection All the Names They Used for God.

Food fight

Every generation of new food technology brings the same question: will this advance do us more harm than good?

November/December 1985



November/December 1997

January/February 2014

From "Getting Off the Pesticide Treadmill": While DDT initiated the new age of pest control, it also spawned a new environmental consciousness. DDT became the principal villain in the problems that emerged as our society began to rely on chemicals for pest control. Soon after the chemicals were developed, questions about their effects on human health and the environment began to surface.

These concerns have proven to be well founded. Many species of insects no longer respond to the effects of pesticides. World pesticide use has increased dramatically, but the percentage of crops lost to pests has not declined. Insects consume as much as one-third of the Asian rice crop annually, and in the United States losses of fruit and vegetable crops from plant diseases may exceed 20 percent. Clearly, just pouring on more chemicals is no answer.

From "Food Irradiation: Will It Keep the Doctor Away?": Nearly 200 people in the US, most of them children or elderly, die each week from illnesses they contract from food. This spring, President Clinton called for "new steps using cutting-edge technology to keep our food safe." One of the technologies that Clinton singles out is food irradiation.

"It will probably take some truly traumatic *E. coli* outbreak before the food industry gets serious about irradiation," says James Tillotson, director of the Food Policy Institute at Tufts University. Without such a crisis, consumers wouldn't think of demanding irradiated food and companies that explore irradiation [would be] open to attacks by activist groups. "No one is willing to get that kind of attention," he says, "even when they might be doing the best thing for consumers."

From "Why We Need Genetically Modified Foods": Plant scientists are careful to note that no magical gene can be inserted into a crop to make it drought tolerant or to increase its yield—even resistance to a disease typically requires multiple genetic changes. But many of them say genetic engineering is a versatile and essential technique. "It's an overwhelmingly logical thing to do," says Jonathan Jones, a scientist at the Sainsbury Laboratory in the U.K. The upcoming pressures on agricultural production, he says, "… will affect millions of people in poor countries." At the current level of agricultural production, there's enough food to feed the world, says Eduardo Blumwald, a plant scientist at the University of California, Davis. But "when the population reaches nine billion?" he says. "No way, José."

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