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Microbe Farmers: How Fermentation Artisans are Bringing Peace to the War on Microbes

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Abstract

In the nineteenth century the French scientist Louis Pasteur proved that the proliferation of certain microorganisms in a host body causes most diseases. His “germ theory” catalyzed twentieth century antimicrobial attitudes, which in the gastronomic realm meant reducing or eliminating microbial activity in food products. Fermentation artisans object that this ongoing “War on Microbes” devalues culturally important food traditions, and misses exciting discoveries that have transformed our understanding of the microverse. Microbes are no longer simply the enemy of food safety – they are the solution to better food. As one cheesemaker put it, “We say that we milk cows, but what we are really doing is farming the microbes.”

This paper presents case studies of science-minded artisans helping Americans move beyond the Antimicrobial Age. Chapter One contextualizes the War on Microbes; whereas fermentation is arguably our oldest food technology, the relatively recent discovery of a microbiological basis for fermentation moved production practices away from the home or farm and into the factory. Chapter Two introduces artisans and their laboratory collaborators, and describes the genomic analytical tools they are using to sequence individual microorganism DNA and RNA (such as for brewing yeast), or to map an entire microbiome (such as for raw milk used in cheesemaking). Chapter Three focuses on wild craft beers, and suggests that lab-domesticated “wild” yeasts are an apt metaphor for the American environmental imagination. Chapter Four profiles a biotech company producing a specialty coffee to illustrate how fermentation is bleeding into biotechnology. Chapter Five visits a creamery in upstate Vermont, where the microbiology of the whole cheesemaking system is essential to an ecological conception of American terroir. The paper concludes with a meditation on the nature of disgust, and a final nudge in the direction of microbial delight.

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Acknowledgements

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Thank you to the entire Graduate Liberal Studies team, but particularly to Donna Zapf, the first welcoming face I saw at Duke (via Skype interview), and my safety net when I unwittingly signed up for an advanced statistics course; Kent Wicker, who taught my first GLS course and sat on my master's examination committee at the very end; and Dink Suddaby, who I suspect cannot be stumped on any Duke-related question, and guided me through my two years here. Thank you as well to my excellent GLS seminar instructors, Amy Laura Hall, Martin Miller, and Martin Eisner; and to Jonathan Shaw, the third reader on my master's examination committee.

I envisioned this paper less as a traditional academic journal article, and more as a longform magazine article, replete with quotes and insider perspectives. To that end I conducted more than a dozen interviews. Every one of my interview subjects generously offered me their time and thoughtful responses: Jim Lahey (Sullivan Street Bakery), Ben Wurgaft (MIT), Camille Delebecque (Afineur), Bronwen Percival (Neal's Yard Dairy), Andrew Durstewitz (D9 Brewing), Mateo Kehler (Jasper Hill Farm), Panos Lekkas (Jasper Hill Farm), Ronn Friedlander (Aeronaut Brewing), John Sheppard (North Carolina State University), Manuel Kleiner (North Carolina State University), Anne Madden (Rob Dunn Lab), Greg Jones (Campden BRI), Catherine Donnelly (University of Vermont), and Chris White (White Labs). An extra thank you to Mateo and Angie Kehler for graciously hosting me for dinner and showing me around Jasper

Hill’s Cellars; and to Cathy Donnelly for allowing me to make her Greensboro inn my Vermont home, with the most perfect fireplace on a cold weekend in February.

These two years at Duke marked a period of personal transition, when I left an editorial job I had held for seven years, moved to Chapel Hill, became a graduate student, and started a literary agency, all at once. I would not have had the courage to try so many new things without my partner Anne Kilby, who also put up with wild pendulations in my sleep schedule.

I was accepted into the GLS program with letters of reference from two brilliant women, Marion Nestle and Darra Goldstein. This project reminded me that food is the most interdisciplinary and challenging of subjects, and I am newly awed by how indominable you both are when faced with tangled threads of meaning.

Finally, I thank my parents, Amy and Ralph, who let me brew beer in their kitchen and hid their panic when the kettle overflowed and burnt the stovetop, or when bottles exploded in the guest bathroom shower. That’s love!

Introduction: E. Coli, the Jekyll and Hyde Bacteria

Google "*E. coli*."[1] What do you see? If your browser resembles mine, your top hits will be the Centers for Disease Control and Prevention (CDC) and FoodSafety.gov websites, highlighting the bacterium's pathogenic potential and cataloguing recent *E. coli* outbreaks. Scroll down further, and the WebMD and Mayo Clinic websites offer tips for recognizing *E. coli* infection symptoms (diarrhea – particularly bloody diarrhea – features prominently), and treatment and prevention protocols (hydrate, wash your hands religiously, and stay away from "risky foods"). Terrifying stuff.

Now Google "applications of *E. coli*." A vastly different set of results appear: "*Escherichia coli* as a Model Organism and Its Application in Biotechnology" (INTECH), "*E. coli* – the Biotech Bacterium" (Science Learning Hub), and "Is There Nothing Science Can't Do With *E. coli*?" (*Popular Mechanics*). Admiring, even fawning articles about the same rod-shaped bacterium.

Certain strains of *E. coli* do pose a public health threat. The most virulent are "Public Enemy No. 1" for the food industry and its government regulators (Neuman 2010a). *E. coli* O157:H7, most commonly found in raw beef, caused an estimated 96,000 illnesses in the U.S. in 2014; of those, only 31 people died, but the associated healthcare costs reached $405 million (Andrews 2014). The threat (and cost) is real.

But it is equally true that most strains of *E coli* are harmless, or even helpful, synthesizing vitamins K and B and aiding in digestion and absorption. Further, this organism has been a godsend for laboratories. It reproduces extraordinarily quickly: its generation time, or the time it takes for the population to double, is twenty minutes. It has a relatively simple genome of only

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[1] I am indebted to Anne Madden at the Rob Dunn Lab for suggesting this experiment.

4,400 genes, compared to 25,000 genes in humans – this is one reason *E. coli* was among the first organisms to have its genome sequenced, in 1997 ("*Escherichia coli*"). It is easily and abundantly found in animal (including human) intestines, fecal matter, and the soil. And it hosts viruses that scientists are eager to study and nourishes other model organisms useful to scientific research. Our understanding of everything from microbial evolution and adaptation, to the mechanisms of genetic exchange in bacteria, to the physiology of bacterial growth, is due in no small measure to *E. coli*.

I am not particularly interested in *E. coli*. What I *am* interested in is the larger truth this Google search comparison reveals: we are living during a transitional, confused, and exciting time in humanity's ancient relationship with the microbial world.

On the one hand, a "War on Microbes" mentality persists that dates back to Louis Pasteur's mid-nineteenth century discoveries linking microbes to infectious diseases. The predictable result of "germ theory" has been an impulse to "eliminate," "eradicate," or "destroy" microbes. We carry Purell in purses, wipe down surfaces with Clorox, and shower sometimes twice a day in the knowledge that germs lurk just beyond sight. We recoil, horrified, from illustrations of petri dishes cultured from the contents of a hand dryer (Astor 2018), or reports of bacteria blasting down on us from our own showerheads (Mann 2009).

In the medical realm, doctors over-prescribe antibiotics to treat bacterial infections, even for earaches and other non-serious illnesses. Antibiotics have helped add twenty years to our lifespans since the discovery of penicillin in 1928; nobody is advocating a return to bloodletting or mercury injections. But the overuse of antibiotics, which non-selectively destroy microorganisms and destabilize our microbiomes, has real consequences. *Clostridium difficile* (*C. diff*), a horrendous diarrheal disease that has become much more common in recent years, is caused when antibiotics destroy healthy bacteria that keeps the naturally-occurring *C. diff* bacterium in check (Langdon, Crook, and Dantas 2016). “Superbugs,” strains of bacteria that have become resistant to antibiotics, pose an existential threat to modern medicine. The threat is so dire that in 2014 the British government revived the Longitude Prize, a three-hundred-year-old challenge that originally asked entrants to figure out how to pinpoint a ship’s location at sea by knowing its latitude. This generation’s challenge asks entrants to help solve the rise of antibiotic resistance, with funding to the tune of ten million pounds (Nesta 2014).

Companies that promise to sanitize our daily lives are invested in this centuries-old War on Microbes. Given my research for this paper, my Facebook and Amazon pages now show a persistent advertisement for a company called Molekule, which claims that the air indoors can be “5x more polluted” than the air outdoors, and helpfully offers a $799 air purifier that promises to “destroys pollutants at the molecular level.”

In the gastronomic realm, where we will reside for the duration of this paper, the War on Microbes has meant a contain-and-control approach to microbial contamination based largely on a pharmaceutical template. Food purity is achieved by using easily sanitized equipment such as stainless steel, strictly controlling all material inputs, and adopting measures to reduce or eliminate the presence of all microbes, such as irradiation and pasteurization. Here again antibiotics appear: they are pumped into the feed of livestock whose meat we eat or milk we drink. A 1980 study suggested that forty percent of all antibiotics ended up in livestock feed (National Research Council 1980); in 2011, that number had increased to more than 80% (John Hopkins Center for a Livable Future 2013). This has led to more antibiotic-resistant bacteria strains, making us paradoxically at greater risk of disease in the long run.

These food purity practices are enforced by a regulatory regime that is all-in on antimicrobial thinking. In fact, “War on Pathogens” is the title of the FDA’s 2016 white paper, which holds food producers and their executives potentially criminally liable for contaminated foods that cause human illness (Food Industry Counsel 2016). With budgets to conduct inspections of manufacturing facilities stretched perilously thin, and *Listeria* rates rising, the thinking goes that manufacturers will be scared into upgrading facilities and self-testing for contaminants if they think they could receive more than a fine for an outbreak.

Listeria, E. coli, and other infections have the potential to be distributed widely in a highly centralized food system. The 2016 Chipotle *E. coli* outbreak, for instance, infected sixty people in fourteen states (U.S. Food & Drug Administration 2016). Food safety regulators (and plaintiffs’ attorneys) will likely be slow to view microbes as anything other than the enemy. Nor could industrial food manufacturers easily change their approach if they wanted to; the industry achieved scale in part by sterilizing foods, thus making them behave predictably. But while industrial food manufacturers are stuck in the Pasteurian past, the rest of us are moving on from the War on Microbes.

Microbes cover virtually every surface of the planet, from underwater volcanic trenches to kitchen counters. Their ubiquity extends to our selves: the very distinction between us and the microbial “other” is illusory. With advances in genome sequencing techniques since the turn of this century we have learned that we are, in a very real sense, symbionts. We carry within us trillions of bacterial cells, and a much smaller number of archaea (single-celled micro-organisms), fungi, protozoa, and viruses (Powledge 2006). One popularly quoted but discredited statistic says that we contain ten times as many microbes in our body as we do human cells. The revised estimate from Israel’s Weizmann Institute of Science is that we contain 40 trillion bacterial, and 30 trillion human cells (Sender, Fuchs, and Milo 2016). Yet the larger point, that we are all living in partnership with microbial communities, is unchallenged. The authors of the Weizmann Institute study hastened to add to their concluding paragraph that "Updating the ratio of bacteria to human cells from 10:1 or 100:1 to closer to 1:1 does not take away from the biological importance of the microbiota."

The discovery of the human microbiota and its many links to human health has engendered a shift in medical messaging regarding microbes. Farah Gilani, a clinician at Forth Valley Royal Hospital in Lambert, Scotland, described this shift in her (2017) article:

> … microbes no longer seem to be as villainous as they once appeared. The concept of the 'human microbiome' forces us to rethink the ideal of being 'squeaky clean'; instead, it appears that a healthy individual is teeming with trillions of 'healthy' microbes. Not only are these harmless, but also they can protect us from the small proportion that are pathogenic and play a crucial role in how our bodies function. (762)

The emergent metaphor governing our relationship with our microbial co-habitants is not of war, but of gardening. As science journalist Ed Yong describes in *I Contain Multitudes* (2016): "Say goodbye to outdated and dangerous war metaphors, in which we are soldiers hell bent on eradicating germs at whatever cost. Say hello to a gentler and more nuanced gardening metaphor. Yes, we still have to pull out the weeds, but we also seed and feed the species that bind the soil, freshen the air, and please the eye" (215). Mateo Kehler, a cheesemaker we will meet in Chapter Five, puts his relationship with microbes in even more agricultural terms: "We say that we milk cows but what we are really doing is farming the microbes."

Anne Madden, a microbiologist who we will spend more time with in chapters Two and Three, told me that when people learn a little bit about microbes, they tend to learn the frightening narratives that the media fixates on: virulent new strains of flu, antibiotic-resistant "superbugs," and "contaminated" showerheads. But when they learn more, they learn about the astonishing biodiversity and ubiquity of microbial life, and it becomes clearer that pathogenic encounters with microbes are rare. “Even pathogenesis… has been described as a ‘relationship’ between host organisms and microbes, which cannot be grouped into strictly ‘virulent’ and ‘nonvirulent’ categories,” writes geographer Mrill Ingram (2011), referencing Swerdlow and Johnson (2002). Mutualism and peaceful coexistence govern our everyday interactions with microbiotas – our own internal ones (our gut and skin microbiota), and external ones (every room we have entered, or woods we have wandered).

I asked Madden where she thinks people are along a continuum, from fear about their pathogenic potential, to admiration or even awe at the unseen work microbes do in our everyday lives. She demurred. “The public is a diverse group,” she said. “Certain communities are excited about the potential of microbes, particularly as microbes relate to their internal microbiome. Others are still fearful or revolted by the concept of microbiological life.” But then Madden offered this romantic template for microbial education:

> Pick your favorite thing in life. If it’s food and drinks, then let me tell you about the microorganisms that make your favorite flavors. They make the flavors of chocolate cake. The flavors of beautiful wines. Your morning coffee. Microorganisms make those moments beautiful.

This paper is my contribution to microbe ardor, rather than revulsion, using the template Madden suggested: food.

Ancient Fermentation

Fermentation in gastronomy refers to any processes that enlist helpful bacteria or fungi to transform and preserve food. There are three basic types of food fermentation: alcoholic (beer, wine, cider, etc.), lactic (cheese, yogurt, sauerkraut, kimchi), and acetic (vinegar). When microorganisms cause undesirable change, such as in the case of rotten milk, it is called spoilage — but one culture’s spoilage may be another’s fermentation (Davidson 2014).

We know that the ability to control and reproduce natural fermentation developed independently on every continent well before commercial trade or meaningful knowledge transfer between cultures. Recent advances in dating organic and inorganic matter offer clues about just how ancient fermentation traditions are. Patrick McGovern, the Scientific Director of the Biomolecular Archaeology Project for Cuisine, Fermented Beverages, and Health at the University of Pennsylvania Museum in Philadelphia, tracks the development of fermentation technologies as far back as the archaeological record allows. Called the "Indiana Jones of alcoholic beverages," McGovern discovered the world's oldest alcoholic beverage, a Neolithic grog from China's Yellow River Valley. Based on chemical residues on clay shards, including a very high concentration of sugars that indicated grape fermentation, McGovern determined that the grog was brewed around 7000 BCE, and was a mixed drink comprised of rice, honey, and hawthorn tree fruit (McGovern et al. 2004).

Paul Kindstedt, who studies the chemistry and crystallogy of cheese with an emphasis on understanding its earliest origins, credits advances in archaeochemistry, archaeobiology, archaeogenetics, and genetic modeling for improving the accuracy of our forensic search for cheese's origins. In *The Oxford Companion to Cheese* he describes how the ability to extract lipids from unglazed pottery vessels changed our assumptions about the timeline for ancient dairying and cheesemaking, just as the ability to extract fruit and grain sugars from unglazed pottery did for beer and wine. Since liquid milk fails to deposit milkfat residues in unglazed pottery under laboratory conditions, Kindstedt assumes milk fats present in western Anatolian pottery shards dating to around 7000 BCE came from a concentrated dairy product, either butter or cheese.

Biomolecular archaeology likewise shifted timelines for fermentation technologies thousands of years earlier in Northern Europe, and showed Nordic peoples to be early experts in fish fermentation. Because of cold and lack of access to salt, an essential ingredient in lactic acid fermentation, ancient Nordic peoples were assumed to have limited contact with fermented foods. But in 2016 a Swedish archaeological team at the University of Lund discovered 200,000 fish bones while excavating a 9,200 year-old Mesolithic settlement in Sölvesborg, Sweden. Nearby the fish bones was an oblong pit, which the team posited was a prehistoric fermentation chamber that used an unusual fermentation methodology: “Because people did not have access to salt or the ability to make ceramic containers, they acidified the fish using, for example, pine bark and seal fat, and then wrapped the entire content in seal and wild boar skins and buried it in a pit covered with muddy soil” (“Signs of Earliest Settlement” 2016).

We can still only guess the origins of fermented foods. Perhaps a Neolithic farmer felt a pleasant buzz after drinking rainwater runoff from his barley silo (Oliver 2011: 435). A North African goat herder transporting milk in a dried kid’s stomach might have found his milk lumpy and tangy after it curdled to yogurt by rennet present in the stomach lining. Mesopotamian foragers could have let wild grapes sit too long in their clay pots, where they turned to mush and fermented to a low-alcohol wine. At best, these are educated guesses.

What we do know is that they shared a common element of chance. From that first observed phenomenon, intentional fermentation proceeded through a process of trial and error. As Selhub, Logan, and Bested (2014) write, “Without knowledge of microbes, our ancestors recognized, over time, the palatability, preservative, analgesic, and mentally stimulating or sedating qualities of fermented foods and beverages” (1).

Modern Artisanship

Today, most brewers, bakers, and cheese-makers have at least some knowledge of the essential microorganisms that help or hinder their ferments. Where we once partnered with microbes blindly, even the smallest farmstead producers now know who leavens their sourdough, or curdles their milk, or sends their wort (unfermented beer) into a bubbling frenzy.

But an influential subset of artisan producers has made microbial exploration their calling. More than acquiring merely a practical knowledge of fermentation, they are partnering with microbiological research labs, or building modest labs to conduct the research themselves. They are learning everything they can about the microbiomes of their products, while hunting "wild" (undomesticated) strains of yeast and other bacteria. They are doing so to introduce novel flavors to familiar fermented foods, to reduce or eliminate their reliance on commercial yeast or bacterial monocultures, and to promote a uniquely American conception of terroir. In some cases, their mastery of fermentation science, and their spirit of microbial adventurism, has become a core component of their brand. These artisans, and the microbiologists working with them, are helping Americans move beyond the "Antimicrobial Age."

In many cases, the artisans themselves are promoting fermentation science and microbe appreciation to the public. But there are also citizen science initiatives from labs researching fermented foods, and magazines, blogs, and other popular media devoted to microbe ardor. I love the Instagram account "under.the.scope," run by Tracy Scott Debenport, a self-described "floof detective," "speaker for the spores," and "microscopy addict." Debenport is a lab technologist at the Wolfe Lab at Tufts. Her boss, Ben Wolfe, is also known for his microbe art.

Fermentation advocacy has entered the cultural zeitgeist. As Dave Arnold, the owner of food and drink research lab Booker and Dax put it, "The cronut is an excellent thing, but it's not fermentation" (Eater Staff 2014). Ben Wolfe and Bronwen Percival, a cheese buyer for Neal's

Yard Dairy in London who we will spend time with in Chapter Two, have teamed up to create MicrobialFoods.org, with a mission of improving “microbial literacy.” Fermentation 101 workshops have sprouted up across the U.S. and U.K., inspired in part by fermentation revivalist Sandor Katz. Fermentation festivals have proliferated to the point where magazines like *Food Republic* write round-up articles about them (Do 2016). This microbial education campaign is being driven by concerns about our industrial food system, growth in the number of artisan food producers (particularly in the U.S.), and a realization that microbes might have many more applications than we realized only a few short decades ago.

This paper presents case studies of fermented food producers whose microbiological research illuminates current attitudes towards the “silent majority” (Handelsman and Smalla 2003). The diversity of fermented foods makes it impossible to cover all of the innovation happening in fermented food production today, so I focus instead on artisans in the U.S., and on only a thin slice of the incredible range of fermented foods.

Chapter One begins by contextualizing the War on Microbes. Whereas fermentation is arguably our oldest food technology, the relatively recent discovery of a microbiological basis for fermentation moved production practices away from the home or farm and into the factory, where microbial sterility was the practical outcome of a drive towards food “purity.” Chapter Two introduces some of the science-minded artisans and their laboratory collaborators who are rehabilitating the humble microbe, and describes the genomic analytical tools that allow rapid strain sequencing and microbiome research in the first place. Chapter Three focuses on the pursuit of “wild” yeasts within the craft beer industry, and suggest that the laboratory domestication of these yeasts is an apt metaphor for the current American environmental imagination. Chapter Four profiles a biotech company producing a specialty coffee to show how fermentation and biotechnology are bleeding together, and to explore the appeal of health claims when marketing the microbe. Chapter Five leaves the food tech world behind to visit a creamery in upstate Vermont, where the microbiology of the whole cheesemaking system is essential to an ecological conception of American terroir. I conclude with a meditation on the nature of disgust.

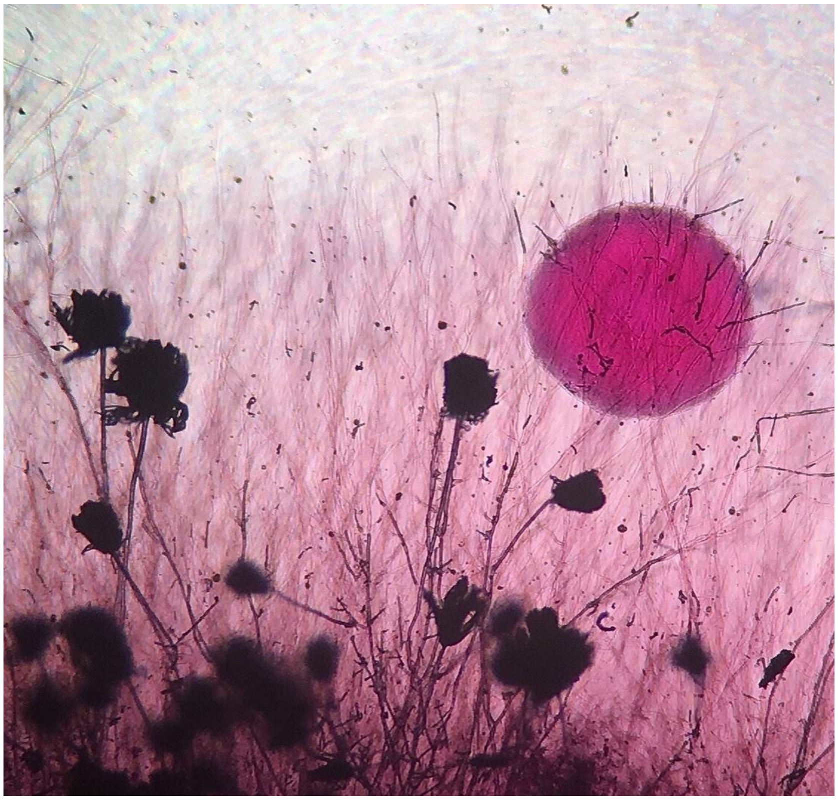

***Figure 1**: “Microbial Sunrise.”* Aspergillus flavus *(fungus) and a yeast colony from a soil dilution plate. Credit: Tracy Scott Debenport*

***Figure 2**: The mold* Sporendonema casei*, which commonly colonizes the surfaces of natural rind cheeses. Credit: Ben Wolfe*

Chapter One: Discovering, and Declaring War on Microbes

Even as the Scientific Revolution unlocked the mysteries of atmospheric pressure, gravity, electricity, and optics, the principles of fermentation eluded discovery because they rested on an entire sub-visible world. Humans can see to about the width of a hair, and a typical fungus hypha is 20-50 times smaller in diameter than a hair. Simple single and multicellular organisms, the oldest life forms on earth, were therefore among the last to be discovered, requiring the relatively late invention of powerful microscopes.

In the seventeenth century, Antonie van Leeuwenhoek, a Dutch textile salesman, built single-lens microscopes capable of magnifying objects up to 270 times. The microscopes were significantly more difficult to use than the prevailing compound microscopes of Leeuwenhoek's day, but his lenses were orders of magnitude more refined. Nobody is quite sure how he managed to grind and polish such tiny, crystal-clear lenses, since he kept his methods a secret until his grave. But in 2015 Brian Ford, a U.K. researcher, demonstrated their efficacy by taking an original Leeuwenhoek microscope from the Utrecht University Museum and magnifying a plate of his own blood using its fiddly, pinhead lens. The photographs he published from the experiment clearly show individual red and white blood cells (Coghlan 2015).

Having perfected his extraordinary microscopes, Leeuwenhoek was relentless about exploring this suddenly visible new world. In 1676 he took droplets from a cloudy glass of pepper water, a thin legume soup, and put them under his microscope. He discovered tiny creatures swimming around, only about one to two micrometers in diameter, which he called "animalcules." In his diary, Leeuwenhoek wrote: "I saw a great multitude of living creatures in one drop of water, amounting to no less than 8,000 or 10,000, and they appear to my eye through the microscope as common as sand does to the naked eye" (Falkowski 2015). The discovery so shocked Leeuwenhoek that he included testimonials from “eight credible persons” who viewed the droplet when he submitted his observations to the Royal Society (Gest 2004: 272).

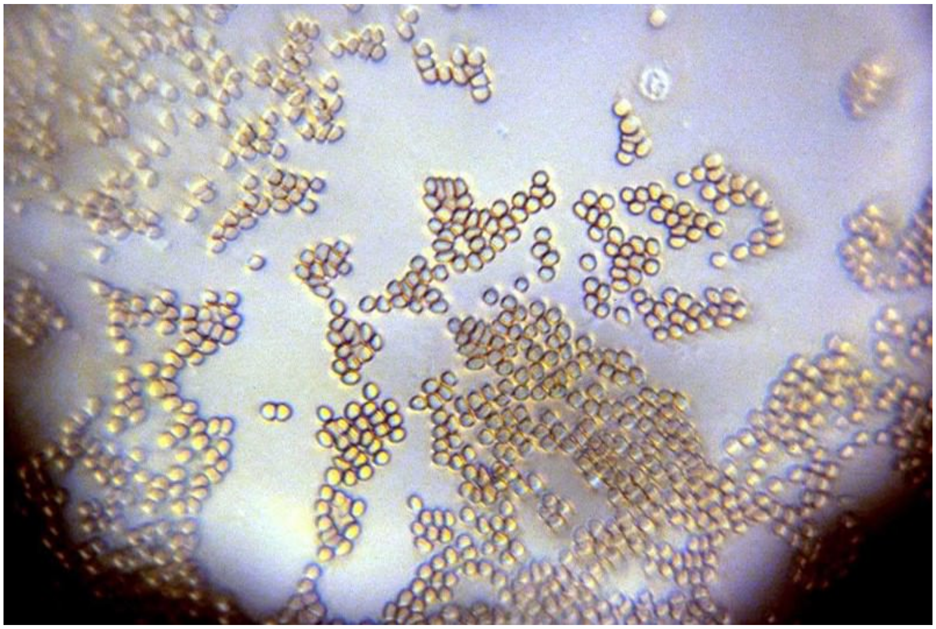

***Figure 3**: Leeuwenhoek’s "animalcules" – in this case, red blood cells and one white blood cell, top right. Credit: Brian J. Ford*

Today we know Leeuwenhoek’s “animalcules” to have been bacteria, sperm, protozoa, and living cells. These he saw in a series of experiments displaying his unbridled curiosity. He discovered bacteria, for instance, by scraping plaque from his teeth. “There was a menagerie in his mouth! There were creatures shaped like flexible rods that went to and fro with the stately carriage of bishops in procession, there were spirals that whirled through the water like violently animated corkscrews…” (de Kruif 1926: 18). Today we name these forms bacillus, or rod bacteria, and spirillum, one of three forms of spiral bacteria.

Leeuwenhoek was also the first to view yeast, having put fermenting beer under one of his famous microscopes. He described them in a 1680 letter to the Royal Society:

> Some of these seemed to me to be quite round, others were irregular, and some exceeded the others in size, and seemed to consist of two, three or four of the aforesaid particles

> joined together. Others again consisted of six globules and these last formed a complete globule of yeast.[2]

Leeuwenhoek understood the globules not as living yeast cells, but as an organic chemical whose presence facilitated fermentation. *The Dictionary of the English Language,* Samuel Johnson's 1755 masterwork, similarly defined yeast in the still-prevailing belief that it was an organic chemical: "the ferment put into drink to make it work; and into bread to lighten and swell it" (Alba-Lois and Segal-Kischinevzky 2010).

In 1779 the French Academy of Sciences posted a kilo of gold for a solution to the "mystery of fermentation," asking: "What are the characteristics which, in vegetable and animal matters, distinguish those which serve as ferments from those which they cause to undergo fermentation?" (Schlenk 1997: 44; Anderson 1989: 338). The reward was rescinded in 1793 during the political terrors of the French Revolution, but inspired reinvigorated research into fermentation science. In 1837, three men independently characterized the role that yeast plays in fermentation. Charles Cagniard-Latour in France, and Theodor Schwann and Friedrich Traugott Kützing in Germany provided "firm evidence that the metabolic activity of yeast cells is the cause of fermentation," demonstrated "that sugar and wort is used for growth and multiplication of the yeast," and properly described "the cytology of yeast cells" (Schlenk 1997: 45).

Much about fermentation remained a mystery, though, chiefly how yeast cells originate – whether they arise spontaneously from inanimate matter, as many believed, or from biogenesis, meaning reproduction, and somehow contaminate the wort (or other fermentation medium). In *Louis Pasteur* (1994), Patrice Debre notes the disconnect between fermentation traditions perfected over thousands of years, and the persistent cluelessness about how it happened. "The

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[2] Leeuwenhoeck, A. *Letter to the Secretary of the Royal Society, 1680*; quoted and translated by Chapman, A. C. *Journal of the Institute of Brewing*, 1931, 37, 433. As quoted in Anderson 1989: 338.

ancient Egyptians brewing beer, the ancient Gauls making their bread dough rise with yeast—these images evoke ancestral practices. Yet scientists, including the earliest chemists, from Paracelsus to Robert Boyle, had no convincing explanation to account for the phenomenon" (88-89).

That situation became increasingly untenable as the Industrial Revolution gained steam, transforming the food industry. Agricultural productivity shot up in the nineteenth century as machines replaced manual labor in planting, harvesting, and processing crops. Better animal nutrition, disease control, and selective breeding increased milk and meat yields. And canning and commercial refrigeration created a global market for food. Food was increasingly assembled in factories, using labor that farm machines had freed up (Hueston and McLeod 2012). Among the first fermented food factories to open were D. G. Yuengling & Son (1829) and the Williams Cheese Factory (1851). For these and other factories to thrive, they needed to create completely predictable and uniform products, which could not be done while fermentation remained mysterious. Enter Louis Pasteur.

Declaring War on the Microbe

The French scientist Louis Pasteur began his career as a chemist, specializing in the then-new field of crystallography, which looks at how atoms are arranged in a solid. He was 26 when he contributed his first major scientific breakthrough. While studying tartaric acid, Pasteur discovered that the acid's atomic arrangement in three-dimensional space, not merely its composition, influences the chemical reactions it undergoes. This not only paved the way for stereochemistry (sometimes called "structural chemistry"), it spurred Pasteur's interest in fermentation; tartaric acid is the primary acid found in grapes and generally controls the acidity of wine.

By his mid-thirties Pasteur was fully immersed in studying biological processes. Beginning in the 1850s, Pasteur linked certain microbes to the diseases they caused, including anthrax, cholera, and rabies. This proved "germ theory," still accepted today, which says that the proliferation of certain foreign microorganisms in the host causes many diseases.

Pasteur didn't just identify the offending microbes – he developed vaccines, and dramatically demonstrated their efficacy. In 1881 Pasteur publicly vaccinated sheep, goat, and cows against anthrax at Pouilly-le-Fort, a small French village. He left a control group unvaccinated; when exposed to anthrax, the control group all died and the vaccinated ones survived.

After such riveting public demonstrations of death thwarted, it seemed entirely possible that all disease could be eliminated simply by studying offending microbes under a microscope, and vaccinating against them, or finding other ways to render them impotent. Pasteur concluded his "Summary Report on the Experiments Conducted at Pouilly-le-Fort" by excitedly noting the universal potential of his vaccination techniques[3]:

> In summary, we now possess a vaccine of anthrax which is capable of saving animals from this fatal disease; a virus vaccine that is itself never lethal; a live vaccine, one that can be cultivated at will and transported without alteration. Finally, this vaccine is prepared by a procedure that we believe can be generalized since, the first time around, this was the method we used to develop a fowl cholera vaccine. (Pasteur 2002: 62)

Louis Théophile Joseph Landouzy, a French neurologist and key figure in the fight against tuberculosis, wrote in 1885 that "the day will come when, thanks to militant, scientific hygiene, diseases will disappear as certain antediluvian animal species have disappeared" (Latour 1988:

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[3] Princeton University historian Gerald Geison studied Pasteur's laboratory notebooks and found that Pasteur actually lied about the culturing technique he used for the anthrax vaccine. In fact, he "borrowed" it from a veterinarian named Jean Joseph Henri Toussaint, who had visited Pasteur's lab and demonstrated the method. ("Pasteur 'Borrowed' From Rival" 1993).

28). Quick advances in bacteriology in Pasteur's later years and immediately following his death in 1895 did effectively eliminate many diseases that had been common in the nineteenth century.

In some sense the War on Microbes preceded Pasteur, though its participants were not clear about the nature of the enemy. Between 1840 and 1920 the U.S. urban population swelled thirty-fold, from 1.8 million to 54 million (Pizzi 2002). Explosive urban growth was also generalizable across Europe, in cities like Paris and London. As the nineteenth century wore on, a movement to improve sanitation in the cities and in hospitals under strain from population growth gained steam. To some degree this "hygienist movement" was motivated by class, with poorer people being seen as a sort of contagion imperiling the health and happiness of the wealthy. In *The Pasteurization of France* (1988), French sociologist Bruno Latour attributes the hygienist movement's origin to the conflict between rising wealth and persistent bad health in urban areas:

> The cities could not go on being death chambers and cesspools, the poor being wretched, ignorant, bug-ridden, contagious vagabonds. The arrival and extension of exploitation (or prosperity, if you prefer) required a better-educated population and clean, airy, rebuilt cities, with drains, fountains, schools, parks, gymnasiums, dispensaries, day nurseries. (18)

The hygienist movement extended not only to public spaces, but to private spaces as well. If you were taught sex ed in school (originally "sex hygiene"), you can thank the hygienists.

The hygienists did not believe in a doctrine of contagiousness, finding abundant examples of healthy people remaining healthy despite their close proximity to sick people, which seemed a counterargument to the prevailing notions of contagiousness. Instead, they believed in a miasma (or anticontagionist) theory of disease, whereby disease arose from foul environments breeding "bad air." And in nineteenth-century cities, there was abundant bad air; not one city in America had a comprehensive sewage system in 1850 (Pizzi 2002).

The hygienists built public health infrastructure like sewage and waste disposal systems, moved slaughterhouses and other factories away from rivers, imposed building codes, and generally undertook what American public health expert Charles-Edward Amory Winslow (1923) called "The great sanitary awakening." This reduced disease and improved life in the cities immeasurably, but because hygienists had no fixed notion of what caused disease – "miasma" and "bad air" being rather vague terms – they were unable to predict or combat specific occurrences of disease. "What was needed," Latour writes, "was a source of forces to explain the astonishing variability of morbidity, its spontaneity, and its local character" (22)

Pasteur's breakthrough was to study tissue and fluid samples from diseased and healthy organisms in a laboratory setting, rather than the site of the outbreak. This was more revolutionary than it first appears. "In 1871 and even in 1880 there was no connection between an infectious disease and a laboratory," writes Latour. "At the time, a disease was something idiosyncratic, which could be understood only on its own ground and in terms of circumstances" (Latour 1988: 62).

Pasteur's astonishing discovery that each disease can be traced back to one or more tiny microbes naturally encouraged a public fixation with the pathogenic potential of microbial life. It didn't help that Charles Darwin had just published *On the Origin of Species*, in 1859. As Ed Yong (2016) writes, "In the shadow of Darwinism, biologists were talking of survival of the fittest. Nature was red in tooth and claw" (35). In that context, peaceful or even mutually beneficial (mutualistic) relationships between humans and microbes that were discovered were overshadowed by villainous ones.

This is apparent in *Microbe Hunters* (1926), Paul de Kruif's classic book about the pioneers of microbiology, which was an inspiration for this paper. De Kruif, a Dutch-American microbiologist, wrote breathless chapters on Leeuwenhoek, Spallanzani, Pasteur, and nine other microbiologists, bacteriologists, and doctors who developed vaccines for rabies, tuberculosis, cholera, and a litany of other eighteenth- and nineteenth-century scourges. But microbes themselves are in some ways the main characters. In his memoir, de Kruif reports that Jules Bordet, a Nobel Prize-winning microbiologist and immunologist who worked with de Kruif at the Rockefeller Institute, told him "Your style of scientific writing is pure… What you should think to do is a *roman des microbes*. I can see you feel they are as much roman as science" (De Kruif 1962: 10-11; as quoted in Henig 2011). That is more or less what de Kruif did, applying a literary sensibility to scientific communication.

In de Kruif's stories microbes are cast as elusive, yet brazen villains, killing villagers just beyond sight of the learned men of science:

> Beasts these were of a kind that ravaged and annihilated whole races of men ten million times larger than they were themselves. Beings these were, more terrible than fire-spitting dragons or hydra-headed monsters. They were silent assassins that murdered babes in warm cradles and kings in sheltered places. (11)

True, de Kruif's microbes are also sometimes the great helpers of mankind, as in the chapter on Pasteur's discovery of the role yeast play in fermenting beer and wine: "The world must know and the people of the world must gasp at this astounding news that millions of gallons of wine in France and boundless oceans of beer in Germany are not made by men at all but by incessantly toiling armies of creatures ten-billion times smaller than a wee baby!" (73). But mainly, de Kruif's microbe hunters are hunting killers.

Pasteur's Gastronomic Legacy

Pasteur came of age during the Industrial Revolution, and his work embodied the nineteenth century's emphasis on applied science. This is especially clear from the partnerships he formed within the food industry.

In Lille, Pasteur helped a beet-sugar distiller fix his sour, un-alcoholic liquor by identifying a proliferation of lactic acid bacteria, and then instructing the industrialist to drain and clean the tank and start over. In Abrois, his hometown, Pasteur saved the wine industry by developing a process for killing contaminant microbes by heating the wine to 55 degrees Celsius. Unlike boiling, this process – "pasteurization" – did not ruin the flavor of the wine.

Pasteur transformed the beer industry by discovering the similar role that yeast plays in beer fermentation as it does in wine fermentation. Open brew tanks, Pasteur found, leave the wort prone to contamination by environmental yeasts and bacteria. In 1870 Pasteur patented a closed fermentation tank that prevented this contamination, and in 1876 he published *Etudes sur la Biere* ("Studies on Beer"), describing how common diseases of beer were caused by contaminating bacteria and yeasts.[4] "Every unhealthy change in the quality of beer coincides with the development of microscopic germs which are alien to the pure ferment of the beer," he proclaimed (Philliskirk 2011). As with the wine industry, Pasteur also developed a pasteurization protocol for eliminating spoilage organisms and giving beer a longer shelf life – up to about nine months – by briefly heating the beer to 131-149°F. Pasteur's patriotic goal was to brew a "Beer of National Revenge" in the aftermath of the Franco-Prussian War; it is debatable whether French breweries ever surpassed German breweries, but his closed brewtanks and pasteurization step unquestionably improved the quality and durability of beer worldwide.

More generally, Pasteur finally disproved spontaneous generation and confirmed that fermentation is due to the reproduction of microorganisms. He did so by an ingenious method. Using a swan neck flask, shaped like an S, he boiled a liquid infusion in the main chamber, killing any microorganisms in it, and preventing new microorganisms from entering the solution

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[4] *Etudes sur la Biere* may have inspired Beer Study, a pub and bottle shop in Durham.

(since they became trapped in the s-curve of the flask). No life arose in the liquid. But when he tilted the flask and allowed the trapped microorganisms to fall into the infusion they multiplied rapidly, demonstrating that microorganisms do not appear spontaneously, but land in food through air- or water-borne particles.

So Pasteur's legacy in the gastronomic realm is mixed. On the one hand, his research on yeast and bacteria led directly to changes in industrial distilling, brewing, and wine-making that reduced inconsistency and waste, and improved flavor. Pasteur's techniques for controlling spoilage and pathogenic microbial contaminants also paved the way for industrialized food production. I don't particularly enjoy single-slice American "cheese" or Wonder Bread, but before we dismiss processed foods entirely, let's remember their benefits. Processed foods generally have longer shelf lives and are more affordable than artisan foods. Wonder Bread may be bland, but to Jim Lahey, the Sullivan Street baker, that's a feature, not a flaw:

> A loaf of bread, a pretzel, focaccia, is either pleasurable or it is not. And you can quantify pleasure: texture, flavor, mouthfeel. Loaves of bread that are really difficult to eat are not pleasurable. That's why Wonder Bread wins, because there is no effort to eat it. Additive-addled bread stays fresher longer. It requires less physical effort… I hate to sound like Freud, but it's the fucking pleasure principle that drives it.

Commodity foods are just *easy*. The cost and time savings associated with their production has also meant lower rates of starvation and malnutrition today compared to Pasteur's lifetime.

But Pasteur's discoveries also mobilized the twentieth century "War on Microbes," which has meant a lingering focus on food purity. Benjamin Wurgaft, an MIT post-doc who studies the anthropology of science, emphasized the sea change Pasteur's work represented, not only for immunology, but also for food hygiene and safety. "Before Louis Pasteur and after Louis Pasteur, we have a decidedly different way of thinking about food and its purity and impurity. People understood that if you had maggots or worms in a piece of food, there was something small that was a problem. But to think of microbial cultures beings responsible for spoilage or change, was something that people had a tacit but not a microscopic knowledge of."

After Pasteur, fermentation, that great writhing around of microbes, was discussed as a kind of infection. In (1903) the Scottish bacteriologist Allan Macfadyen gave a speech at the Institute of Brewing in London titled "The Symbiotic Fermentations" that repeatedly called mixed-culture fermentations "mixed infections." For Macfadyen, the actions of yeast and typhoid bacteria (later identified as *Salmonella typhi*) ran parallel: "Broadly considered, in each of these cases, we are dealing with an infection, the suitable soil furnishing the means for the development of the special activities of the organisms in question" (4).

Post-Pasteur, the challenge with fermented foods became how to make such an inherently unsanitary-seeming mode of food production "sanitary." Each industry had its own techniques, but generally speaking, they included pasteurization or irradiation, using commercial starter cultures in lieu of ambient microbes, and using stainless steel and other easily sanitized equipment in lieu of traditional wooden equipment that harbored microbial communities.

Beer provides a good case study of how this food purity mentality transformed a traditional fermented beverage into a commodity liquid. In the twentieth century, brewers used increasingly innovative means to hide the appearance of yeast in bottles, and later cans. These methods included centrifugal filtration and using fining agents such as isinglass, gelatin, and Irish Moss to remove spent yeast and other sediment by binding to the molecules and dropping them out of the solution. This forms a clearer, brighter, more consistent beer in flavor and appearance. Brewers also adopted artificial carbonation technologies, sometimes called forced carbonation. Traditionally, CO_2 is a natural byproduct (along with alcohol) of the yeast fermenting the wort. Sometimes this is helped along in the bottle by adding some sugar to perk the yeast up after they are exhausted from the primary fermentation, referred to as bottle-conditioning. Forced carbonation, by contrast, directly injects pressurized carbon dioxide into the beer. At the turn of the twentieth century Pabst pioneered a technique to capture the excess carbon dioxide from fermentation, removing the yeast and all sediment from its lagers, and then direct-injecting carbon dioxide back in. Other breweries quickly adopted similar methods, which a circa-1940s P. Ballantine & Sons Brewery schematic reveals:

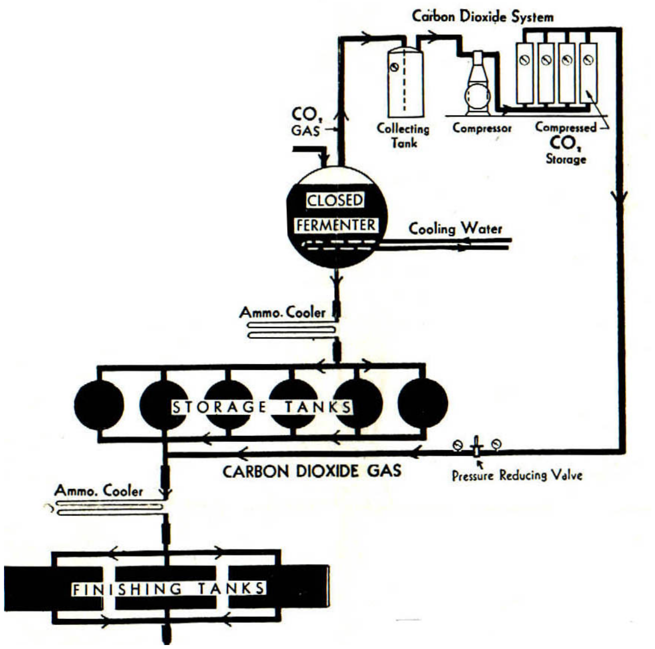

Figure 4*: An early twentieth century schematic of the Ballantine and Sons brewery, showing a carbon dioxide capture step.*

These industrial purification and sanitation regimens made fermented foods seem risky when produced outside of factories. Whereas pickling, brewing, and cheesemaking were common homestead and local artisan activities in the nineteenth century, in the twentieth century most people left these pursuits to larger commercial interests. The loss of artisanship was not limited to developed nations with industrial food production; in a globalized economy, cheap factory versions of traditional fermented foods drove out artisan producers worldwide. In *Wild Fermentation*, Katz cites an admiring 1977 report by Clifford W. Hesseltine and Hwa L. Wang at the USDA Fermentation Laboratory regarding Coca-Cola's efforts to sell Africans a factory version of Bantu beer, a traditional alcoholic beverage made from malted millet. The initial recipe was unsuccessful, but Coca-Cola soon isolated and domesticated the yeasts and bacteria found in local brews and produced a version "using modern malting and fermentation equipment." What grates at Katz is the assumption that the factory version is inherently superior to local versions of Bantu beer. "A cheap and uniform product, mass-produced under sanitary conditions, is taken as unequivocally superior to the traditional village-produced product, regardless of the cultural and economic importance of the practice in the village context" (Katz 2012: xxi).

This is not to minimize the necessity of food safety reforms in the wake of Pasteur's research, which undoubtedly saved countless lives. For instance, the rapid population growth of urban areas in the nineteenth century meant that milk was often pooled from many farms and shipped hundreds of miles by rail, with poor or no refrigeration. Unsurprisingly, milk became a major vector for tuberculosis, pneumonia, and other zoonotic diseases, as just one farm's contaminated milk could quickly spread throughout a centralized distribution system. Early twentieth century "clean milk" movements in the U.S., UK, and elsewhere eventually forced regular testing of dairy herds, the pasteurization of liquid milk intended for human consumption, and stricter criminalization for selling adulterated or tainted milk.

But the low microbial load counts allowed by regulators in important fermentation inputs like milk, and the twentieth century focus on food purity and uniformity, came at the cost of both the flavor and range of fermented foods. Artisans, for whom skilled labor takes precedence over mechanical or automated production technologies, by definition cannot match the consistency of factory outputs. Nor would they want to: part of the ethos of "artisanship" – a loose term that lumps together interrelated terms like "craft," "local," "traditional," "farmstead," and "non-industrial" – is what David Pye, a British furniture maker, once called "a workmanship of risk" (Pye 1968: 7; as quoted in Paxson 2013: 132). Artisans work with their hands, leaving room for both human skill and human error to affect the quality of the final product. The industrial process, by contrast, is a "workmanship of certainty" where you know exactly what the process will produce.

With fermented foods, part of the workmanship of risk is how adroitly the artisan partners with his or her sub-visible helpers. Most of the twentieth century badly devalued that partnership by casting microbes as the enemy of food purity, when fermentation is nothing without microbes. In *Food & Cooking*, the American food writer Harold McGee estimates that over a dozen species of bacteria once involved in making yogurt have disappeared; today, industrial yogurts have only two or three bacteria, namely *Lactobacillus bulgaricus* and *Streptococcus thermophiles* (McGee 2004; quoted in Ingram 2011: 111). Nor is that loss of microbial diversity easy to reclaim. Mirjana Curic-Bawden, the senior scientist at the Danish company Christian Hansen, whose bacterial cultures ferment about forty percent of all yogurt sold in the U.S., says that even ostensibly heirloom, home yogurt cultures are descended from store-bought yogurts, "which in turn came from the bacterial collections of companies like Christian Hansen" (Charles 2015).

Bronwen and Francis Percival, co-authors of *Reinventing the Wheel: Milk, Microbes, and the Fight for Real Cheese* (2017), blame a culture of obsessive hygiene incompatible with artisan cheesemaking for a loss of tradition, terroir, and flavor in American and European Union cheeses. "Milk has changed. The past thirty years have seen a holocaust of raw-milk microbes. This is not a term that we use lightly: the quest for control has caused the catastrophic destruction of the microbial communities on which cheesemakers rely to make their raw-milk cheeses distinctive and unique" (95). In Chapter Five, I discuss how artisan cheesemakers are waging a public campaign to preserve their right to make traditional, unpasteurized ("raw") milk cheeses. They do so with science on their side. Pasteurization, like chemotherapy, wipes out good and bad microbes alike in milk. Without a healthy community of good microbes to keep pathogenic ones in check, pasteurized milk is particularly susceptible to downstream recontamination. This is one possible reason why a study of U.S. outbreaks attributed to cheese between 1998 – 2011 found that outbreaks were more common in cheeses using pasteurized milk than in those using unpasteurized ("raw") milk (Gould, Mungai, and Behravesh 2014).

As recently as 2011, the environmental writer Mrill Ingram wrote that we remain stuck in an antimicrobial, Pasteurian age, despite the good PR that should come from delectable fermented foods:

> Microbes, of course, have been recognized as critical in making bread rise, beer ferment, and cheese blue. Understanding this role in culinary achievement has not, however, translated into a wider appreciation for microbial diversity and behavior and their critical role in our ongoing good health. (107)

I do not believe Ingram's analysis remains true in 2018. Regulators and lazy journalists may still see microbes mainly as potential pathogens, but an increasing number of artisans view them from a utilitarian perspective, as powerful tools to achieve better flavors, mouthfeels, or any number of other desirable qualities. And a DIY pickling, homebrewing, and even home cheesemaking movement has gained ground. A 2017 survey conducted by the American Homebrewers Association estimated that there are 1.1 million homebrewers in the United States (Armon 2017). Like Katz, they are conscientious objectors to the War on Microbes.

Microbes, in short, are no longer just the enemy of food purity and safety – they are also the solution to better food, as we will see in the next chapter.

Chapter Two: Cellular Gastronomy

In 2017 Jim Lahey, proprietor of Sullivan Street Bakery in Manhattan's Hell's Kitchen and inventor of a legendary no-knead sourdough recipe, successfully baked bread using the corpse of a wasp that had died of dehydration in his attic. In an article in *Taste* magazine that detailed his unusual sourdough starter (sometimes called a "mother"), Lahey came off as an educated eccentric: "[H]e once noticed a Pliny the Elder reference to fermentation involving wasps. The baker wanted to know if this held up in practice. So Lahey—ever the mad scientist—mixed water with the corpse of a dead wasp" (Weissman 2017).

That article glossed over his practical intuition in favor of highlighting his classical inspiration. It was true that he had read Samuel Fromartz's *In Search of the Perfect Loaf*, which references ancient Roman philosopher Pliny the Elder's use of a wasp in making a leavening. "But then I noticed a memory of having an outdoor pizza party in upstate New York," Lahey told me in his characteristically quirky phrasing. "When we were setting up, putting the doughs out, the flours, all this other stuff, the sky opens up. We ran into the house, leaving everything outside. The next day there is a cup filled with water and flour, and I see all these wasps feasting on it. Then a day later, I'm watching the same cup of flour and water, fermenting spontaneously, seething, bubbling. Aha!"

Certain species of wasps, it turns out, store *Saccharomyces cerevisiae* in their abdomen over winter. Which made perfect sense to Lahey. "Half the problem with humanity is never looking in the right place. We look where we think we should be looking. But the wasp is equipped to cause the rotting and fermentation of fruit on trees. It precipitates it. It assists it."

Lahey has no scientific training. What he knows of the alchemy of fermentation he learned over thousands of hours perfecting sourdough, rye, pumpernickel, and other recipes. Yet, like many chefs, bread bakers, cheesemakers, and brewers today, Lahey professes a love of microbiology. “I would consider myself a cellular gastronomist, not a molecular gastronomist,” Lahey told the *New York Times*. “I’m always thinking in terms of microbes and populations of microbes” (Smith 2012).

In 2012, Lahey had his sourdough starter sequenced by Rachel Dutton, a microbiologist who runs a lab at Harvard. Lahey nourished the starter to life in 1992 from a culture taken off the leaf of a dinosaur kale plant plucked in the Italian countryside. Yet Dutton determined that it contained only a single bacterium, *Lactobacillus sanfranciscensis*, a species of lactic acid bacterium named for the city most associated with sourdough breads. Most sourdoughs globally feature the same bacteria. “I was heartbroken. I wanted to believe that my sourdough was the most special sourdough in all of Italy,” Lahey told me.[5]

Despite the slight initial letdown, Lahey eagerly awaits an approaching “golden age of fermentation,” when science will hand him extraordinary tools for improving his already-famous sourdough. That golden age might be close at hand, thanks to a new generation of microbe hunters. They are in search not of the disease-causing microbes responsible for cholera, tuberculosis, or typhoid, but those that form microbial communities that in some way improve on traditional fermented foods.

Making Wasp Beer

Anne Madden is a chipper postdoctoral research fellow at the Rob Dunn lab at North Carolina State University, whose icebreaker revelation (I hope) is that she was inducted into the Luxuriant Flowing Hair Club for Scientists™ in (2015). Madden calls herself a “microbial

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[5] He perked up a moment later when *Lactobacillus sanfranciscensis*’s universality inspired him to come up with a new slogan: “Bread everywhere, for everyone. Bread in Mozambique. Bread in Lima. Bread for all!”

explorer" and "microbe wrangler," by which she means that she collects environmental — "wild" — microbes and then develops ways of harnessing them to solve human problems. Lately, she's been fixated on the problem of bland beer. The vast majority of beers are brewed with one of two yeast strains: *Saccharomyces cerevisiae* (ale) or *Saccharomyces pastorianus* (lager). These monocultures (pure, single-strain yeast cultures), which can be ordered from a lab or purchased at any homebrew store, deliver consistent results and are some of the most well-researched microflora on the planet. But as technologies for detecting the microbial biodiversity of environmental samples have improved, Madden wondered: could there be yeasts out there that are just as effective at turning maltose sugar into ethyl alcohol, while possessing other characteristics desirable to brewers, such as novel flavor compounds or better mouthfeels?

The entirety of nature is an overwhelmingly vast place to go bioprospecting for beer yeasts. As Handelsman and Smalla (2003) complained, "If only bacteria would howl, cheep, squawk, trill, purr, or rustle, how easy would be the job of the microbial ecologist!" But Madden had the same insight that Lahey had: to use her knowledge of evolutionary adaptations to guide her to places likely to support abundant yeasts. "We know that yeasts have incredible sweet tooths: they can be found uniquely in environments that are high in carbohydrates, high in sugars. These environments can be nectar. They can be rotting fruit. They can be tree sap. They can be in your soda the next day after a party."

Those are ephemeral and, in some cases, inaccessible locations for microbiologists working in labs. But Madden also knew that, unlike bacteria or filamentous fungi, yeasts are not particularly mobile. They compensate for their immobility through a beautiful, and predictable, form of mutualism:

> One of the solutions yeast have evolved to this problem is to catch a ride on insects, particularly those sugar-feeding insects that are going from sugar location to sugar

> location. They have evolved the ability to withstand being either inside the body of a wasp or bee, or with some yeasts, they create structures that make them better at grabbing hold or sticking to the outside of an insect. And there seems to be this relationship that the yeast are producing aromas, in the form of fruity and floral esters, and alcohol, that may also attract insects. These insects are not just acting as an airplane carrier for the yeasts, but are actually using the yeast to find sugar sources.

With that ecological and evolutionary context in mind, Madden began searching the microbiomes of paper wasps for promising yeasts. She found several, isolated them, extracted their DNA, and compared them to a reference database of existing beer yeasts. The goal was to find a new species, but one that was still similar to existing beer yeasts. If the yeast belonged to a genus that was unable to break down maltose, the primary sugar in beer, or that was unable to produce ethanol, then it would never be able to ferment beer.

Ultimately Madden found not just a new beer yeast species, but an entirely new genus. Whereas before there were only two known genera of yeast capable of brewing beer, *Saccharomyces* (including the ale and lager sub-species) and *Brettanomyces* (common mainly in sour beers), now there is a third: *Lachancea*. “We added 50 percent, a whole third genus,” says Madden. “So that’s really fun, because it opens up the possibility that there are many more lineages of yeast that are capable of making beers and that potentially we were limited by our assumptions, not by our technology.”

Madden turned the yeast over to John Sheppard, a bioprocessing professor at North Carolina State University, and the brewmaster at the university’s brewery. He used it to brew a sample batch based on an Extra Special Bitter (ESB) recipe, which, in hindsight, he says “was not at all appropriate for this yeast.” Sheppard, who is not a fan of sours, tasted it and was unconvinced of its potential. “I thought it was godawful.”

But Sheppard and Madden had already committed to bringing their “wasp beer” to the Science of Brewing tent at the World Beer Festival in Raleigh, which in 2014 overlapped with the North Carolina Science Festival. Sheppard brewed and kegged a full batch on NCSU's 2.5-barrel system; to his delight, the festival-goers loved the taste, and the story behind it. Madden isolated more strains of the same wild yeast genus from a bumble bee; appropriately, it produced a very sweet beer that people swore had honey in it. Bumble Beer earns high marks on beer rating sites like Untappd; more brews, and presumably more strains of *Lachancea*, are on the way.

Artisans like Lahey and microbiologists like Madden embody a spirit of exuberant microbial exploration that is transforming fermented food production. They are at the forefront of a growing awareness that fermented foods, like human beings, are microbiomes, communities of organisms co-existing under the umbrella of a familiar name, like "beer" or "cheese" or "bread." This is not exactly new news; we have, after all, understood the basic microbiology of fermentation since Pasteur's research in the mid-nineteenth century. What is different today is the

***Figure 5**: John Sheppard pours a taster of Sour Mineola Ale, an unreleased beer brewed with Lachancea yeast and mineola orange peels.*

availability of tools for measuring the incredible biodiversity of microbial life, and for capturing interactions among microorganisms in fermented – really all – foods.

Measuring the Microbiome

The earliest tool for detecting microbial communities was the microscope. Leeuwenhoek's refined lenses made him the first to view yeasts, bacteria, and other microorganisms. Microscopy remains an important tool in microbiology, but it is limited in terms of detecting species variation. Manuel Kleiner, who studies microbiomes and complex microbial communities at North Carolina State University, says that teeming masses of microorganisms are hard to distinguish under a microscope. "It all pretty much look the same. You know, just different shapes, but not really." New techniques help maintain microscopy's relevancy; for example, Kleiner's lab uses fluorescence probes that bind to microbes on a species-specific level. "The fluorescence is really bright, Kleiner says, "and automated software can take pictures and then count how many microbes there are of one color in contrast to another color."

But the more powerful tools available for measuring fermented food microbiomes today use genomic sequencing and are direct descendants of the Human Genome Project (HGP). That initiative cost $2.7 billion and took a decade, from HGP's launch in 1990 to the completion of a first draft in 2001. The work depended on the Sanger sequencing approach, a manual method that was limited in terms of cost and speed. After the HGP's final report in 2004, the National Human Genome Research Institute (NGHRI) planned an aggressive, $70 million initiative to bring the sequencing cost of a single human genome down to $1,000 in ten years (Reuter, Spacek, and Snyder 2015). Since then, the cost has been in free fall, touching $1,000 in 2016.

Several companies have developed commercial technologies to sequence any organism's DNA at higher volume and greater speed. A San Diego-based biomedical company called

Illumina has been the most successful, bringing to market a series of increasingly low-cost "desktop" sequencers in reach of even small labs (Fikes 2018). Illumina and its competitors, as well as contract labs, which sell DNA sequencing and analysis as a service rather than selling equipment, have found a burgeoning market for their technology among fermented food producers.

Recent research collaborations between commercial labs and food producers and their suppliers showcase the enthusiasm for genomic testing within fermentation-reliant food industries. In 2017, for instance, Illumina worked with White Labs, a major supplier of brewing yeasts, and two Belgian universities to sequence and phenotype 157 industrial *Saccharomyces cerevisiae* strains (Gallone et al. 2016). Their purpose was to investigate how industrial ("domesticated") yeasts have evolved differently from naturally-occurring ("wild") yeasts. They found that all industrial brewing yeasts can be divided into five sub-lineages originating from only a few domesticated ancestors, and that this domestication predates microbiology, possibly as a result of backslopping, the practice of using old beer to inoculate new ones. "…'backslopping' might have resulted in yeast lineages that grew continuously in these man-made environments and lost contact with their natural niches, providing a perfect setting for domestication" (1397).

The results were fascinating to academic researchers, but also effectively marketed Illumina's sequencers to the 5,300+ breweries in the U.S., and tens of thousands more internationally, interested in better understanding their own yeast strains. Illumina's press release about the findings made the commercial implications clear:

> "A lot of brewers struggle with consistency," said [Senior Lab Manager] Steffy. "If you scale up, the beer never really tastes the same. A lot of that could have to do with the yeast. Maybe it doesn't handle bigger batches. You can make choices that are going to serve you well if you're planning to scale up."

> Even better, the genomic info could give brewers greater control over their beer, allowing them to target yeast(s) that produce the most desirable traits.

The study was published in the prestigious science journal *Cell*, and was also accepted in *Nature*. Chris White, the founder and owner of White Labs, mused to me that Illumina got more than they bargained for. “I think if [Illumina] knew that it would get published in *Cell* they would have been super ecstatic. That combination of a lot of strains with high throughput sequencing really created great results. And that’s just the beginning, because there are a lot of labs that saw that, and now they are using more Illumina instruments, buying more. I see our work cited almost every week.”

Illumina’s collaboration with White Labs highlights the power of so-called next-generation sequencing technologies, which can rapidly sequence whole genomes. Whole-genome sequencing analyzes every single bit of DNA in an organism, rather than referent segments, capturing small variants in the genome that would have been missed in coarser sequencing technologies. It can provide exceptionally granular analyses of the sort that ten years ago would only have been available to public health and university research laboratories.

Whole genome sequencing is extremely useful to White Labs, and by extension, to its customers, mainly breweries, distilleries, vintners, and kombucha-makers. White Labs is primarily a yeast bank, collecting and storing thousands of brewing, distilling, wine-making and kombucha-brewing yeast strains, and packaging and selling some of them for home or commercial use. A large part of their business is storing private strains for customers, promising that the strains will be accessible to them at some point in the future, healthy and without genetic drift. “It’s a lot of husbandry, taking care of these strains so they don’t change, making sure we have good cryogenic freezes,” White says. And whole-genome sequencing is a game-changer on the verge of widespread adoption. “The instruments are still very expensive, but within just a few years I believe this is the technology we will all have. And how great will it be to say, ‘Has my yeast changed? Oh let me put it into my Illumina, and I’ll know exactly the genetic change that might have happened.’”

White also identifies a major benefit to knowing exactly what yeast strain was there in the first place. “When people find something new, or send us in a private strain, right now there is no way to really verify if it already exists in our bank or if it is truly novel. With this kind of sequencing there would be no secrets.” In a sense, what is happening in the obscure world of yeast banks reflects what is happening in the more public realm of human genealogy, with companies like 23andMe and Ancestry already offering affordable DNA testing. “It is surprising a lot of people,” says White, with just a touch of good-humored schadenfreude, “because they have relatives they never knew about. People have secrets, but the DNA doesn’t lie. It’s fun to see that working its way through the human pool of information. And it’s really going to be cool to apply this to industries like brewing.”

We’ve established why genomic sequencing is extremely useful in comparing individual yeast strains. But what if you want to do a full microbiome analysis of your food product, or a material input, such as the milk used in cheesemaking? Then it is the interaction among many organisms in a community that counts. But here, too, the tools are becoming much more powerful, and much less expensive, thanks to metagenomics.

Conventional sequencing relies on culturing a colony of identical cells. But scientists who compared microscopy to lab cultures of the same sample realized they often did not match in terms of the number or variety of microbes, a phenomenon J. T. Stanley and Catherine Konopka (1985) called “The Great Plate Count Anomaly.” We now know this is because many microorganisms cannot easily be cultured; for instance, some estimates suggest that less than one percent of all soil microbes are easily culturable (Ingram 2011: 99). Early efforts to sequence the microbiomes of fermented foods thus underestimated their biodiversity. Metagenomics uses polymerase chain reaction (PCR), a technique that amplifies small segments of DNA by several orders of magnitude to more accurately capture the collective ("meta") genome ("genetics") from an environmental sample – one can simply sequence everything one finds in, say, a puddle, a thimble full of seawater, an ancient thigh bone, or a wasp corpse.

As with conventional DNA sequencing, metagenomics analysis was initially quite expensive, but has come down significantly. Producers today can have a microbiome analysis done for a few hundred dollars. Panos Lekkas, the chief scientist at Vermont creamery Jasper Hill Farm, who we will meet in Chapter Five, told me that "You can get about 100 gene extractions for about $250."

Testing Fermentative Fables

Microbiome population analysis is still a luxury for most small-scale producers, and even those who have access to this information may not find a practical application for it. Rachel Dutton's printout of the microbial composition of Jim Lahey's sourdough starter culture made for an interesting read, he says, but it did not change a thing about how he baked. He meant to set up pH testing to instruct others on how to tell when the dough is ready to shape and bake, but he never quite got around to it, and the Sullivan Street bakers still do it all the old-fashioned way – by smell, feel, and sight.

Nevertheless, microbiome research on fermented foods is quietly changing production practices. In 2012, Lahey was among a select few to have had his sourdough starter sequenced. But today, at least 1,000 more people globally can boast the same privilege. In 2017 the Rob Dunn Lab invited people worldwide to send in samples of their sourdough starters (Rob Dunn

Lab n.d.). The Dunn Lab, in conjunction with the Wolfe Lab at Tufts, then used metagenomic testing to discover all of the microbial species that exist in these starters. Their findings were overlaid onto a Google Map, showing the zip code for each starter, the starter's age, and the yeast and bacterial taxonomies ("taxas") present in the starter (Nichols and McCoy n.d.).

The crowdsourced data have already yielded valuable clues about sourdough starter biodiversity. Lahey, it seems, had reason to be (mildly) disappointed that the bacteria in his starter consisted entirely of *Lactobacillus sanfranciscensis*. It is indeed a common bacterium in sourdough starters, but nowhere near as dominant as previously thought. "What we're finding is that there is a fantastic diversity of yeast and bacteria that are making these starters possible and we're looking at all sorts of different factors that can explain this variation," says Madden. "We're looking at some of the human components: how people are treating their starter, what they're feeding their starter, where the starter originated, and other global ecology questions."

Modern bakers and brewers know that fermentation is a metabolic process caused by microorganisms consuming sugars and producing organic acids, gases, and alcohol. But there is an element about fermentation that remains mysterious, and speculative beliefs about fermentation have taken root over centuries. In the case of sourdough starters, everyone seems to have a secret formula. Some swear that you need fruit – pineapples and grapes are popular. Others believe that the location in which you nourish your starter to life determines its composition. Still others think sourdough starters reflect something essential about the baker handling it.

Now that we can sequence the microbiomes of fermented foods, we can test these beliefs. Dunn's lab, for instance, was fascinated by the baker-starter link hypothesis, as the introduction to The Sourdough Project indicates: "The *Lactobacillus* bacteria… play a key role in starters, include species known from human bodies. *Lactobacillus* bacteria inhabit vaginas, guts, and even, sometimes, armpits and belly buttons. It is entirely possible that when you make a starter that the particular *Lactobacillus* that you seed it with are your own symbionts. But how could we possibly know?"

By experimentally testing it, of course. The Dunn Lab, again in collaboration with the Wolfe Lab, sent out the same flour to bakers all over the world, and asked them to create a starter from it. The bakers who responded were then invited to bring their starters to one location in Belgium, where scientists from the lab sampled it, as well as the bakers' hands and the resulting bread they baked, to see if they could derive that link between baker and bread. The lab is analyzing that data now. In the meantime, Madden has already modified the pipeline she uses to strategically find brewing yeasts, to instead find baking yeasts. "There are yeasts that can make bread that have valuable characteristics to the industry," says Madden, "and we've started to license these yeasts to some of the major bread producers."

Cheese is another area of intense interest for microbiome analysis, with immediate practical applications. During my research for this paper, employees at both Jasper Hill Farms in Vermont and Neal's Yard Dairy in London mentioned that they had been contacted within the prior two weeks by contract labs in the U.S. and U.K., offering sophisticated metagenomics testing. Bronwen Percival, the cheese buyer at Neal's Yard Dairy and the co-author of *Reinventing the Wheel: Milk, Microbes, and the Fight for Real Cheese*, was contacted by Campden BRI, a British contract lab that specializes in science and technology solutions for the food and drink industry. "They came to me asking about high-throughput DNA sequencing to look at the authenticity of cheeses: do they come from a particular farm, a particular place?" That forensic application could be useful for, say, Italian retailers trying to determine whether unscrupulous cheese producers or middlemen are passing off Grana Padano as Parmigiano Reggiano. But it did not interest Percival, since cheese fraud in the U.K. is less common.

Another application did interest her, however: high throughput microbiome analysis of the raw milk used by Neal's Yard Dairy's suppliers. Up until now, those suppliers, mainly small farmhouse cheesemakers specializing in British and Irish territorial cheeses, have relied on a relative index test to analyze their milk. This test was specifically designed for cheesemakers, as Percival describes in *Reinventing the Wheel*:

> Instead of using DNA analysis to identify all the organisms in a sample, they use old-fashioned culture-based methods to quantify members of each of the broad groups of microbes – the lactic acid bacteria, the other Gram-positive bacteria that can play a role in cheese ripening, and the Gram-negative bacteria – as well as the total yeasts and molds. This doesn't reveal the names of the individual species, but at the farming level, such names are little more than trivia. Through relative index testing, even a farmer with just ten cows can gain access to information about the microbial community within his or her milk. (107)

What Campden BRI offered was far more exciting. In fact, Percival sounds downright giddy when she started talking about the potential of whole-genome metagenomic analysis: "If we could have a snapshot of the biodiversity, the different genera present in the sample, and then the relevant amount of each one, that's so far beyond what you can get with a relative index test, it's amazing. That's the holy grail of being able to monitor your milk microbial communities!"

The cost is not inexpensive, but Percival says it is manageable. "[Campden BRI] could do it for about £60 a sample, and they have to run 100 samples at a time, so that becomes £6,000, meaning we have to find a way to get ten producers together, testing multiple samples to make it worthwhile. But if they can freeze their milk [for transport] and we can make that work, then there is no reason that we can't use this really cutting-edge thing that would have been the stuff of science fiction even for hardcore scientists twenty years ago, and *certainly* totally out of our reach even three or four years ago, to run some trials."

Even that level of microbiome analysis does not represent the population testing that may soon become available. Metagenomics is still fundamentally a counting tool, and counting tools are problematic. Kleiner, the NC State microbiologist, showed me a presentation he gave at a biotech conference illustrating why. “Nature can have these 6000-fold differences in terms of the mass [of microorganisms]. I mean, really huge differences.” He clicked to a slide showing dozens of small green cells and two or three very large red ones. “If we count all the members by species and then get this distribution, the green ones that are very little here make up a lot in terms of abundance. But if you actually look at their masses you see the distribution would be very different.”

Kleiner’s lab has developed a new technique for measuring the *biomass* of microbes in a community, rather than simply their abundance (Kleiner et al. 2017). The technique relies on metaproteomics, meaning the identification and quantification of proteins (rather than DNA) in microbial communities. Metaproteomics has traditionally been used to measure microbial activity, since proteins in cells are really what drives metabolic activity. “We get as many proteins identified and quantified as possible and then we say, ‘Oh, species X must be eating sugar, and species Y must be eating carbon dioxide.’” Kleiner’s insight was to recognize that proteins also form most of the biomass of simple organisms. “If you subtract all the water, half of the mass of all organisms is protein and then the rest are snippets of DNA and other things. So protein is really a good proxy for most organisms to get an idea of how much mass they really have.”

Kleiner’s biomass assessment technique uses an enzyme to slice proteins into fragments, called peptides, and then a computer to sort the peptides into known organism genomes. The result is a far more nuanced analysis of a microbiome. “Most current microbial community studies are like a census of what types of microbes are present in a community and how many, which provides some good basic information… our technique can be likened to interviewing the neighborhood residents to figure out more about who they are, what they do and how much they contribute to their community," Kleiner told *NC State News*. This biomass assessment technique has been tested successfully on an artificial microbial community, one in which Kleiner's lab knew beforehand all of the microorganisms in it and their abundance. That's promising, but further testing is needed.

In the meantime, the analytical tools that contract labs are increasingly offering to fermented food producers are plenty sophisticated. Greg Jones, the microbiologist at Campden BRI who is working with Percival, explained to me a few applications for their "Advanced Microbial Profiling (AMP)" kit. "Fermented foods such as cheese have many claims made about the effects of [their] microflora, such as flavour profiles and health benefits. The ability to create a detailed profile of the microflora gives the producer a way to prove more comprehensively than ever before that those claims are valid."

That still seemed abstract, so I asked Jones for actual examples of how artisans are using AMP testing. He responded:

> We are currently working with two raw-milk cheese producers to look at how changes made to the bedding and housing conditions of cows affects the raw milk microflora. The producers wish to know if the raw milk flora is affected by these different conditions, and if so to then track these changes through to the final cheese to examine their effect on flavour. If a particular set of conditions results in a superior cheese, AMP can then be used to monitor the microflora to ensure that this is replicated in further batches.

What AMP and other testing kits promise to quantify is the impact of traditional fermentation practices on the microbiological profile of the final product. "Until recently it hasn't been possible to examine the microflora with more depth, which will help us to understand why the good practice already in place results in the desired product," says Jones. With more sensitive and robust microbial population surveys like AMP, artisans are able to empirically say why, for example, a mottled, goopy raw milk Camembert de Normandie tastes so much better than its fluorescent-white industrial counterpart. That gives artisan producers ammunition to defend their traditional practices from regulators still insisting on a War on Microbes, as we shall see in Chapter Five. For now though, let's dive deeper into the craft brewing industry and its use of wild yeasts.

***Figure 6**: Dr. Manuel Kleiner in his office at NCSU. He gets grief from colleagues about the Duke-blue walls.*

Chapter Three: Taming Wild Yeasts

D9 Brewing is about three miles off the east coast of Lake Norman, North Carolina's veritable inland sea. It was formed in 1963 when the Duke Power Company built its eleventh hydroelectric dam along the once-mighty Catawba river. Founded in 2014 by two engineers and a doctor, D9 is engaged in its own efforts to tame nature, albeit on a microscopic scale. Its proprietors specialize in the wild-fermented sours that have added mouth-puckering acidity to the craft beer flavor revolution. But if wild yeast is the conceit, control is the reality when it comes to D9's sours. "We science the shit out of beer," says Andrew Durstewitz, the CEO and Co-Founder of D9 Brewing, channeling Matt Damon in *The Martian* (Borchelt 2017).

Earlier this year D9 launched Pearadox, the first in their "Taming Wild Beasts" series of sours. It was fermented using a *Lactobacillus* bacteria strain from the *Calluna vulgaris* flower, a shrub common to Scotland's bogs, with additions of Bosc pears and pink Himalayan sea salt. Deployed in a D9 beer, *Lactobacillus* is about as wild as Lake Norman: the bacteria were carefully selected, rigorously tested, and added to wort designed to match the bacteria's temperature, acidity, and sugar content preferences. The bioprospecting work was done in a small on-site lab with a "microscope, spectrophotometer, lots of chemicals and of course tons of spreadsheets," says Durstewitz. (D9 also has access to Sierra Nevada's much larger lab.)

Eight hundred miles northeast of D9, in Somerville, Massachusetts, Aeronaut Brewing also celebrated its opening in 2014 with a "chair-anaut launch": red, white, and blue balloons carried a picnic chair high above the brewery as drones shot footage. Like D9, Aeronaut exudes scientific adventurism. It was founded by a computational biology Ph.D. student at MIT, a biotechnology Ph.D. student at MIT, a biology Ph.D. student at Yale, and a computer scientist. They began as homebrewers, albeit unusually analytical ones. "A lot of what appealed to me was the engineering part of it," says Ronn Friedlander, the biotechnologist. "Building temperature controls, doing side-by-side experiments at home, with different hops, different methods, different temperatures." Soon they'd cobbled together a 60-gallon brew system from Craigslist, featuring a prison cafeteria kettle. The roommates realized they needed to sell beer to justify the purchase. With their life savings and the help of investors — including MIT professors — they built a brewery, and upgraded their equipment again, to a bigger (and less jerry-rigged) brew system.

From the outset Aeronaut had a yeast research lab, tucked away behind pallet storage. But as their identity as a brewery specializing in wild-fermented beers developed, they built a larger, more visible lab ("Aeronaut lets its beaker flag fly" 2016). There, they unboxed new toys: "shaking incubators, a spectrophotometer, a laminar flow hood, gel boxes and a PCR machine." Friedlander, whose doctoral research involved biofilms (collections of microorganisms that adhere to a surface), put his experience isolating and culturing microbes to good use. "Right off the bat we had some wild yeast we were experimenting with." The strain that Aeronaut has been most successful with was taken off a flycatcher held up to the wind on top of a local fire tower. Friedlander cultured it into trillions of cells and named it Genghis Khan, for the fecund first Mongolian Emperor. "It's never become a mainstream production yeast," says Friedlander, but we've done a Belgian double with it that's very popular when we have it, and an American wheat ale."

Other beers claiming microbial wildness are proliferating. Wisconsinite, brewed by Lakefront Brewery in Milwaukee, features "a unique, first-of-its-kind, never before fermented, indigenous Wisconsin yeast strain" (Wisconsinite Sell Sheet n.d.). Urban Funk Wild Ale, brewed for a short time by Two Roads in Stratford, Connecticut as part of its "Captured Yeast" series, touted a stew of wild yeasts captured during Hurricane Sandy (Urban Funk Wild Ale n.d.). "The result is a totally unique, totally funky beer experience indigenous to our own backyard," the website reads. (One might wonder whether commercializing "hurricane yeast" was in good taste. Or how "indigenous" the yeasts could be in the midst of a category 3 hurricane that blew across 24 states, Canada, and the Bahamas. More on that later.)

And then of course there is the paper wasp and bumblebee yeast that Madden discovered, and which John Sheppard brewed with. Wasp Beer and Bumble Beer proved so popular that Sheppard and the Rob Dunn Lab patented its application in brewing. North Carolina State University owns the technology, but it is not set up to commercialize it; the NCSU brewery has only a 2.5-barrel system, where craft breweries often have 10-barrel systems or more. So Sheppard formed a company, Lachancea LLC, after the yeast's scientific name, and licensed the rights from the university, in order to sub-license the rights to craft breweries. He has four customers: Deep River Brewing in Clayton, Gizmo Brew Works and Nickelpoint Brewing in Raleigh, and Ecusta Brewing in Brevard.

With American craft breweries increasingly experimenting with "wild yeasts" and other wild microbes like *Lactobacillus*, it is worth parsing what microbial "wildness" means in a brewing context, why craft breweries are interested in microbial bioprospecting, and what message consumers are taking away from it all.

What "Wild-Fermented" Means

Up until the development of commercialized yeast strains in the late nineteenth century, all beers were in a sense "wild." What control pre-modern brewers exerted over the fermentation derived mainly from backslopping. Generation after generation effectively passed brewing yeast from batch to batch without knowing the strain of yeast responsible for the fermentation, or even that yeast was involved at all. “Yeast” is nowhere to be found in the Reinheitsgebot, the famous German beer purity laws first enacted in 1516, because Louis Pasteur was still more than three hundred years removed from discovering the crucial role yeast plays in beer fermentation.

Before modern sanitation, lactic acid bacteria, acetyl bacteria, and environmental yeasts like *Brettanomyces* would, to varying extents, sour every pre-modern beer, which is why sour beers have been called the “original beer style” (Stanger 2014). But one practice particularly exposed wort to contamination by souring microbes: fermentation in long, shallow trays called coolships (*koelschips*). (The “ship” derives from the early use of hollowed-out tree trunks, resembling canoes) (Philliskirk 2011: 265.) The practice arose from the need to cool boiling hot wort quickly, or the bubbly magic would not commence; we now know this is because yeasts die off at high temperatures. Before mechanized refrigeration was invented in the mid-nineteenth century, one way to cool the wort before casking it was to pour it into large shallow trays, letting physics go to work on the increased surface area. This left the wort open to being dive-bombed by any passing microbe, making the beer flavors unpredictable, and giving “wild-fermented” beers their name. Over time, breweries in the Senne Valley region of Belgium, near Brussels, fully embraced the individual batch-to-batch character of these wild-fermented sour ales, called lambics, to the extent that they placed their coolships in the roofs of their breweries, near shutters opened to welcome microflora.

These lambic producers – including producers of gueuze (a blend of young and old lambic), kriek (cherry lambic), and framboise (raspberry lambic) – developed natural techniques to manage the coolship chaos. They deployed – and still deploy – an army of spiders to keep flies away from the wort. Some lambic brewers believed the spiders also trapped the fermentation microbes in their webs. “The more likely scenario,” writes Daniel Kvitek, a geneticist who has studied naturally-occurring yeasts, “is that the microbes for lambic fermentation live in the porous wooden beams and fermentation vessels inside the brewery” (Kvitek 2011: 844).

The microbial communities, called biofilms, that develop on the wood surfaces of lambic brewing equipment and in the brewhouse itself influence the beer character and give some degree of batch-to-batch consistency. Mrill Ingram (2011) describes these biofilms as cities, “heterogeneous assemblages of various bacterial species that create communities by shifting lifestyles from nomadic, unicellular individuals to sedentary, multicellular groups” (103). One study that sampled two fermentation batches over a two year period at Catillon, a traditional Belgian lambic producer, found over 2000 bacterial and yeast isolates, with a relatively stable microbiome in both samples despite being taken a year apart (Spitaels et al. 2014). The study concluded that “Although minor variations in the microbiota between casks and batches and a considerable species diversity were found, a characteristic microbial succession was identified” (1). The authors also took DNA “fingerprints” from the brewing environment, and successfully identified bacteria including “*E. hormaechei*, *E. kobei*, *Es. coli*, *H. paralvei*, *K. oxytoca*, *Citrobacter gillenii* and *R. terrigena*, from which some of these were already detected in the cooling tun sample, suggesting their origin from the cooling tun environment” (10). In other words, the bacterial communities sampled in the wort as it cooled in the coolship – “cooling tun” is just another word for coolship – reflected the composition of the biofilm communities that had formed on the wooden equipment in which the lambic was brewed.

The importance of these biofilms cannot be overstated: not only do they help produce a relatively consistent product, despite the use of spontaneous fermentation, but they also give lambic producers a claim to terroir more commonly associated with wine producers. Because of the unique biofilms, lambics from different breweries can have very different characters, giving them place-specificity. It is obvious then why lambic producers dread replacing rotted wood panels or discarding old brewing equipment (Graber-Stiehl 2017).

Traditional lambic producers still operate today. Places like Cantillon in Brussels and De Troch in Wambeek ferment in coolships, eschew starter cultures, and age their beer in open wood casks (usually oak) for a period of one to three years. But by the late nineteenth century most breweries adopted closed, stainless steel equipment that could easily be cleaned and sanitized; defined their inputs carefully, including using pure yeast and bacteria monocultures; and produced styles that could be brought to market quickly, which in the U.S. meant lagers.

The modernization began with Louis Pasteur's research on beer yeasts and his 1870 patent for a closed fermentation tank. The Danish mycologist Emil Christian Hansen then built on Pasteur's research by successfully isolating a pure bottom-fermenting (lager) yeast cell in 1883. Hansen was working at the time for Carlsberg Brewery, and was able to roll out pure culture yeasts for Carlsberg's lagers later that same year (Anderson 1989: 343). *Saccharomyces pastorianus* (lager) and, later in the twentieth century, *Saccharomyces cerevisiae* (ale) monocultures came to dominate the brewing industry.

These domesticated strains evolved in the U.S. under selective competitive pressures from the mega-breweries that emerged out of Prohibition. Between 1919, the onset of the Volstead Act, and 1933, the Act's repeal, Prohibition precipitated a catastrophic industry collapse. In *The Oxford Companion to Beer*, Pete Brown writes that "Of the 1,392 brewers in operation before Prohibition, only 164 remained afterward" (671). The ones that did survive consolidated, until only large factory breweries remained. Each mega-brewery's "house" culture of *Saccharomyces cerevisiae* or *Saccharomyces pastorianus* was virtually identical. "In the twentieth century, 99.9 percent of all beer was made with the same yeast," says Sheppard. "They wanted blandness, high alcohol yield, essentially no flavor, and very reproducible, fast fermentation." Over time the industrial house cultures were modified, and their precise character kept secret. But all industrial house yeasts today are variations on the same theme: consistency.

"Wild-fermented" came to mean the antithesis of this commercial, monoculture fermentation. In the U.S., "wild" became a category descriptor for the sour beers that were imported from Germany and Belgium in the late 1990s, and that are now imitated by a growing number of American craft breweries. Initially, consumers were slow to catch on, confused by the tart flavors unlike any other ale. "We still get customers who call to let us know a bottle of our barrel-aged beer had gone bad because it tasted sour," Vinnie Cilurzo, the owner of Russian River Brewing Company in California told the *New York Times* (Burningham 2010). But those with a taste for sours really preach their gospel, as DeBenedetti's 2013 *New Yorker* article captured:

> Sour beer lovers sometimes speak of being ruined on conventional beer styles—forever. It must be love. Or is it lightning, bottled? The ions of acidic foods, it turns out, can penetrate the cell walls of our tastebuds, triggering an electrical response, exchanging free radicals, like our skin in the open ocean.

Sour beer popularity has continued to grow unabated, a subplot of the American craft beer revival. Revenue from the sale of gose, a German sour style, increased 1,000 percent in the U.S. from 2015 to 2016 (Jacobsen 2017).

American craft brewers like D9 and Aeronaut chase this consumer interest in sours, but they cannot realistically re-create the traditional brewing conditions developed for sours in Belgium and Germany. (A small handful of breweries, like Allagash Brewing in Maine and Russian River Brewing in California, have experimented with modernized coolships.) For one thing, they do not have the stable biofilms built up over a century or more; nor do they have the wood surfaces on which those biofilms develop. For another, wild microbes easily spread throughout the brewing environment, turning *all* beers to sours. Pasteur would roll over in his grave if he found out brewers were welcoming yeasts like *Brettanomyces*, which can linger for years, even in low-nutrient environments.

Contamination by wild microbes does not pose much of a health risk to consumers, since the alcohol content generally makes beer aseptic. The risk is more economic. The heart of the craft beer revolution is variety. Breweries pivot frequently between styles and recipes, keeping only a few beers in their core rotation and making the rest seasonal or specialty brews. It wasn't always like this, as Chris White related:

> There might be a brewery that would use a wheat beer strain, but they were a wheat beer brewery. There might be a brewery that would use a sour yeast, but they were a sour brewery. In the late 90s, early 2000s, you had people saying, "You know what, I'm going to make a wheat beer." So they would buy the wheat beer strain. And then they said, "I'll make a lager." So they bought a lager yeast. Now a brewery doesn't just make one thing. Even big breweries are making lots of different things.

A *Brett* infection that spread throughout the brewhouse would imperil that brewery's ability to produce, say, a blond ale *alongside* a sour.

Finally, few modern breweries can stomach the flavor and quality fluctuations that result from truly spontaneous fermentation without the steering help of biofilms. D9 is not one of them. "We forage microflora from fruits and flowers, cultivate those strains through exhaustive isolation techniques, identify the most flavorful strains, classify them through PCR testing, variance test them for ester creation and then finally train them for efficient wort fermentation," says Durstewitz. What breweries like D9 – whose tagline is "The Art and Science of Wild/Mixed Fermentation" – mean when they market a wild-fermented beer is often simply that they used non-standard yeast strains. They do *not* mean the use of coolships, ambient yeasts, or biofilm-laced wooden brewing equipment. Where "wild-fermented" and "spontaneously fermented" were analogous for much of the twentieth century, today "spontaneously fermented" beers constitute a tiny percentage of the wild beer category, almost exclusively brewed in Belgium and Germany.

Not everyone is comfortable calling fermentation by lab-cultured yeasts “wild.” Chris White suggests that as a category descriptor, “wild” is a confusing catch-all. “There’s probably a better term for it, because it’s like, here’s this brewing-range yeast, and here’s everything else. You want to call *everything else* wild?”

John Sheppard, meanwhile, objects to the term on ontological grounds. He believes that true wildness is only possible in an open fermentation: “A pure-culture fermentation, where you have isolated a yeast, grown it up in a pure culture, and eliminated any other yeast from your fermentation, is not a wild fermentation. Even though the yeast has a wild origin, it is not wild fermentation. Wild fermentation to me would be, you leave the fermenter open.”

Friedlander is likewise uncomfortable with the way “wild-fermented” is being used, even by his own brewery. I asked him to define “wild-fermented,” and he began confidently in the same vein as Sheppard: “To me, if you are going to call something a wild ale, I guess that it should be truly wild, in the sense that you are not necessarily controlling the cultures that you are putting in.” But then, he faltered:

> I don’t know… there are certain points where you might say is this wild or not? Like if you had something that was a wild ale, and then you got a good beer out of it, and then you took the dregs of that ale and used it to inoculate the next beer, is that still a wild ale? I would say, yea that’s still a wild ale, at least by our definition. But, I think the second you start bringing it into the lab and purifying it…. Well I don’t know maybe that isn’t fair, because we have wild yeasts that we are purifying…

Friedlander concluded with a verbal shrug. “I guess it is very different than working with brewer’s yeasts!”

Bioprospecting for wild beer yeast and other useful microbes in brewing is indeed very different than working with commercial monocultures. Screening to find the right microbes from environmental samples, or even knowing where to pull the samples in the first place, is laborious. It involves getting lucky with the sample, isolating and growing yeasts in petri dishes, charting acidification and saccharification trends, and, for the most promising few, brewing time-consuming sample batches. Friedlander described the difficulties of this work:

> It requires a certain amount of expertise, and equipment. So you really have to devote resources as a company to it, when it's not really, or in any obvious way, a revenue-generating thing. And it's not a quick process. You get certain flavors from wild yeasts, and you often find ones that are not pleasant. It requires patience to collect enough yeasts, choosing the ones that work.

Friedlander went on to describe how a yeast with suitable brewing characteristics (for instance, the ability to convert sugar into ethanol) will sometimes still produce a bad initial batch of beer. "Sometimes we find, if you keep re-pitching the yeast, it adapts to the environment." But that coaxing process takes time and resources, two things that are in short supply in the ultra-competitive craft beer industry.

Sheppard likewise highlighted the time and effort involved in successfully deploying wild yeasts, even after their discovery. He finds the term "bioprospecting" misleading because it projects an image of gold flashing in a pan, when the reality is that bioprospectors don't immediately know when they've found something valuable. "With yeast and microbes, you isolate them, but then the work has just begun. It's not like you can immediately say, 'Oh, I struck gold here!' Maybe you find that out six months down the road, but there is a lot of stuff you've got to do between the discovery and the evaluation of it."

Lachancea, the yeast species that Madden isolated off of a paper wasp and that Sheppard developed into a sour beer, is about as close to a gold-strike as one gets in the world of beer yeast prospecting. It is rare for a yeast to produce significant quantities of organic acids; in lambics and most sours generally, it is lactic acid bacteria or acetobacter (which produces acetic acid) that gives the acidic flavor, not the yeast. *Lachancea* produces organic acid. This has major commercial implications; it typically takes at least six months to make a sour beer, and part of that is a secondary fermentation, when brewers add lactic acid bacteria. *Lachancea* can make a sour beer in about three weeks, without the secondary fermentation. “That’s a *ridiculous* change in timeline,” says Madden, representing a potentially large cost savings to brewers.

But even still, using a wild yeast like *Lachancea* requires a good deal of work on the brewer’s end. That is because wild yeast strains don’t behave like commercialized monocultures. “Traditional brewing strains are very vigorous, very consistent, predictable. Honestly you can abuse them *a lot* and they will still perform,” says Sheppard. “So they are much easier. You don’t have to know much about the yeast in order to be able to use a typical brewing strain.”

***Figure** 7: Sheppard in front of the yeast propagator that he built at NC State's brewery.*

There is also a lot less information available regarding wild yeasts if anything goes wrong. “Any information that you know is basically self-developed,” says Sheppard. “You have to discover it yourself, and that’s a long learning procedure.” His knowledge was hard-won; four years after bringing the wasp beer to the World Beer Festival, he has only recently become comfortable brewing with *Lachancea* commercially.

And then there is the danger of brewery-wide contamination by *Brettanomyces* and other wild yeasts. To counter that possibility, craft brewers experimenting with sours take precautionary measures. Avery Brewing in Colorado, for instance, built a negative pressure room for storing their oak barrel-aged sours, to prevent contamination of their other beers (Wallace 2015). Here, too, Madden and Sheppard were lucky with *Lachancea*, since it does not outcompete *Saccharomyces.* “This is a very gentle wild yeast,” says Madden. “It behaves like a domesticated strain.”

The finickiness of wild yeasts, the lack of information about them, and the risk of contamination are why wild yeasts have been used mainly by craft breweries, not macro (industrial) breweries. For macro breweries, the last century of brewing has been about making yeast convert sugars into alcohol extremely quickly, consistently, and with a minimal addition of flavor. Sheppard doesn’t see that changing any time soon. “They are not going to want to adjust the way they do things. Which is necessary for these wild yeasts, honestly.” To underscore that point, Sheppard tells me he has invested on average three to four months working with each of his four brewery clients before they were confident enough to brew with *Lachancea* on their own. “They don’t know how to manage it, what kind of conditions or recipes, all that.”

Which begs the question: if using “wild” microbes is this difficult, why use them at all? Sure, there is an economic incentive, in that breweries want to meet consumer demand for sour beers. The trendiness of sours, most fermented with yeasts in the *Brettanomyces* genus, was satirized in an April Fools article in *Craft Beer & Brewing Magazine* titled "Brewers Brace for Brettanomyces Shortage." A despondent brewer moans that "All of our funky beers are now going to be made with Chico yeast. I mean, there's nothing funky about Chico" (Holl 2018).

But while sour beers are undoubtedly hot, the volume of sour beer sold in the U.S. is still a tiny fraction of the total volume of craft beer sold. There were 245,000 cases of sour beer sold here in 2016; by contrast, there were 14.5 million cases of IPA sold in the same period (Gajanan 2017). The growth is real, but perspective is needed.

In part, it comes down to a competition for flavor. In a three-part blog series titled "Yeast Shepherding," Friedlander lays out the math: 4,000 breweries (actually more like 5,300+ now), brewing in 114 style subcategories recognized by the Beer Judge Certification Program, means each style is crowded with beers. "[A] search for "IPA" on Beer Advocate gives nearly 16,000 results. Even searching for one of the more esoteric styles, 'sahti' yields twenty commercial examples. If the thousands of craft breweries want to try something new, we'll have to be very creative" (Friedlander 2016).

The pressure to innovate is immense. Beer has four main ingredients: hops, malt, water, and yeast. Brewing with different hop varietals has been a major source of flavor differentiation in recent years, with most serious beer geeks able to name at least a few common hops, such as Mosaic, a fruity, citrus-y hop popular in single-hopped IPAs; and Cascade, the most widely used hop in American craft breweries, which lends spicy and flowery flavors and aromas to pale ales and lagers. Some hops are even the centerpiece of a beer's brand: Mosaic (Pelican Brewing Company), Mosaic (Terrapin Beer Company), Mosaic IPA (Community Beer Company), and Mosaic Promise (Founders Brewing Co.) are just a few of the many beers that feature – you guessed it – Mosaic hops. Sorachi Ace, a Brooklyn Brewery beer I'm fond of, is named for a Japanese hop varietal notable for its lemongrass aroma.

Malt, too, has been an area of innovation in recent years. Brewers are incorporating a wider range of grains, such as oats or rye instead of (or in combination with) the traditional barley; roasting malts to give coffee-like or chocolatey flavors; and using sensory diagnostic tools like those offered by DraughtLab to more accurately describe malt flavors.

The mineral content of water — the water's "hardness" or "softness" — can give subtle flavor differences, though few breweries advertise their water source. An exception is the Czech beer Pilsner Urquell, the original pilsner-style blond lager, which has long marketed its "soft Pilsen water."

Perhaps the biggest change to beer flavor profiles in recent years has been an explosion in adjunct ingredients, such as chilies, peppercorn, orange peels, pumpkin, and ginger. But it is difficult to think of much that hasn't already been added to beer. When you start seeing beers brewed with bull testicles (Ferner 2012), or with crushed lunar meteorites (Coxworth 2013), you are scraping the bottom of the proverbial adjunct barrel.

Everywhere we look, though, we find new strains of brewing yeast, only a tiny fraction of which have made it into wort. Wild yeasts promise novel flavors and aromas, better mouthfeels, and other valuable qualities in the race for craft brewers to differentiate their products. "In the very near future," says Madden, you're going to see consumers asking what yeast their beer was made with" (Graber-Stiehl 2017).

But there are practical hurdles to overcome, beginning with the general aversion people have to microbiology. "I see a lot of resistance to microbiology even among the brewers," White says. "They kind of have to be microbiologists because they are in the beer industry but they really want to not be. But it would be great if consumers knew more about yeast. Then they'd know more about the beer they were drinking, just like brewers who handle yeast better make better beer."

White Labs does not generally sell wild yeasts; rather, they curate established alcohol-producing yeasts that have been collected and shared between yeast banks worldwide since soon after Emil Christian Hansen isolated a pure yeast cell in 1883. The very biodiversity of wild yeasts that excites brewers, also presents marketing challenges. "There are a lot of wild yeasts that most people, even those who are into wild beers, would have never heard of, because they are not going to be in a lot of beers," says Friedlander. "They are going to be in one beer by one brewery. So I don't know that those are going to be mainstream, unless there is a new wild yeast that just hits it out of the park."

Madden doesn't buy these arguments. She points out that the hops beer geeks are so conversant in are strains, a sub-level of species. "You have the same framework that you do with yeast: there's an incredible difference in taste based on that strain level variation and the brewing world has no issues keeping that catalog of twenty, forty, however many hops there are," says Madden. And catchy names are not exclusive to hops – consider Aeronaut's most prolific wild yeast, Genghis Khan.

Sour-oriented breweries, tasting rooms, and bars are already marketing yeasts at the genus or species level. Wicked Weed's Funkatorium in Asheville, North Carolina, for instance, has a long list of "Brett farmhouse ales," meaning *Brettanomyces*-fermented farmhouse ales. The future, Madden argues, will belong to strains:

> You can already walk into a sour brewery and ask, "oh are you guys using pedios [*Pediococcus cerevisiae*] or lactos [*Lactobacillus*] in your sour beer fermentation?" And some people will start reveling in that knowledge, and that's just going to increase. If it is a house yeast strain, that's fine, but the techniques available to understand what that

> house strain is are available. People are going to start requesting things that they like that they didn't have language for before, and that's going to involve the microorganisms.

Madden's vision is one of microbial and linguistic abundance. If you are unimpressed by just the latest chili-flavored IPA or passionfruit witbier, well, good news: there is an entire unseen world out there for brewers to colonize and pour into your glass.

In a way, wild-fermented beers are an apt metaphor for the entire American environmental imagination. We no longer have the illusion of limitless natural resources, but we crave abundance. We've domesticated the planet, but we long for the wild.

Microbes, the Final Frontier

America is a frontier nation that no longer has a frontier. That has been true in a literal sense since the Treaty of Guadalupe Hidalgo in 1848, and the subsequent Gadsen Purchase of 1853 that gave the U.S. ownership of its westernmost territories, all the way to California and the Pacific. But our influence on every place and every living thing today is so extensive that, as Jedediah Purdy argues in *After Nature: A Politics for the Anthropocene* (2015), "the familiar divide between people and the natural world is no longer useful or accurate" (2). In the Anthropocene – the term coined by biologist Eugene F. Stoermer to describe human activity's dominance over the current geological age – humanity has shaped things both immensely large (the warmth of the planet, the height and acidity of our seas) and astoundingly small (the DNA of life itself, or the precise microbes that ferment your beer).

Purdy argues that there are at least four traditions of environmental imagination in America. There is the Puritan providential vision of wilderness as something to conquer, a moral test from God. Puritan sermons frequently riffed on the idea that pilgrims were "God's Gardeners," reclaiming Eden from the wilderness. Explosive population growth at the turn of the twentieth century and the completion of Manifest Destiny then inspired a Progressive utilitarian vision of wilderness as a store of wealth for America’s citizens. America’s forests and fields should bring prosperity to everyone, not just a chosen religious few. In the nineteenth century a Romantic notion of wildness developed, inspired by the Romantic literary movement. Contact with wild places was thought spiritually nourishing and epiphany-producing, prompting the Sierra Club’s efforts to preserve some wild lands as public parks. This culminated in the mid-twentieth century with the 1964 Wilderness Act that initially protected nine million acres from development, and now protects twelve times that number.

Finally, the twentieth-century environmentalist movement revealed nature to be a more complex system than ever imagined, wherein DDT used to kill mosquitos could somehow end up endangering fish and fowl. “The heart of ecological nature is interconnection so deep and widespread that boundaries among organisms, places, and systems are neither stable nor secure,” writes Purdy (41). It is this last, ecological imagination that defines our current age of conservationism and environmental management. Another term for it is holism, the idea that ecological communities are so tightly bound together by forces of codependence that examining their component parts without reference to the whole interconnected web of life is impossible (Levins and Lewontin 1994).

But stepping up to that systems level is profoundly depressing, because climate change and widespread extinctions reveal the limits of our conservationism. The 2015 Intergovernmental Panel on Climate Change’s business-as-usual scenario predicts a 2.4-foot rise in sea levels by 2100, which would devastate coastal cities, while the five hottest years on record have all happened since 2010 (Kennedy 2018). Meanwhile, dozens, perhaps hundreds of species of plants and animals go extinct every day, with one study predicting 30 to 50 percent of all species could wind up extinct by mid-century (Center for Biological Diversity n.d.). Elizabeth Kolbert, a staff writer for the *New Yorker*, termed this loss of biodiversity the “sixth extinction” in her 2014 Pulitzer Prize-winning book of the same title. Biologist E.O. Wilson’s Half Earth Project frames the risk of mass extinction in dire terms: “Only by committing half of the planet’s surface to nature can we hope to save the immensity of life-forms that compose it.” We don’t know how bad things could get, and that is terrifying.

An ecological conception of nature is also depressing because it lacks the romantic notion of wildness we yearn for. Biology, the study of all living organisms, has evolved to systems biology, which biotechnologist Joan Fukimura describes in his essay “Technobiological Imaginaries” as the study of “gene networks, cells, organs, and organisms as systems interacting with each other and with their environment” (Fugimura 2011: 77). The same is true across the environmental sciences, from soil sciences to climatology. Systems-based approaches lead to mechanistic metaphors. Fukimura describes how technocratic big science projects at the end of the twentieth century introduced machine analogies to systems biology:

> The human genome projects of the end of the twentieth century enabled the collection of masses of information… To make knowledge of the collected information, however, researchers are searching for other tools, a change in methodology and epistemology. Some systems biologists are attempting to provide rules and principles to organize these bits of information into systems that help to explain the function and dysfunction of organisms. (77)

Nature is increasingly understood in engineering terms, comprehensible only through rules and principles taken from artificial intelligence, robotics, mathematics, and even chemical engineering, and modeled using large data sets and computer software.

Earlier conceptions of nature were defined by a more personal relationship to wildness. Reclaiming wildness was a providential calling to the Puritans, the wild lands promised limitless natural wealth to the frontier settlers, and the solitary wildness of the Rockies gave life meaning for the Romantics and later wilderness advocates. But wildness, meaning places free of human influence, are a fiction today. The wilderness that the Pilgrims encountered has been “reclaimed” from the Pacific to the Atlantic (Native Americans might say stolen), there are limited natural resources left to extract, and even fewer untrammeled vistas. Where is the wildness we yearn for in a systems-based conception of nature?

In her forthcoming book *Banquet in the Ruins*, the environmental anthropologist Gina Rae LaCerva describes this loss of a sense of “wildness” from a gastronomic perspective:

> Two-hundred years ago, half the American diet consisted of wild foods. Hunting and gathering were associated with poverty and subsistence. Today, most people will never eat anything undomesticated, and “foraged” flavors and “gamey” flesh are increasingly a mark of wealth, refinement and purity. The top restaurants in the world serve weeds to their elite clientele.

The popularity of “wild” foods, LaCerva argues, is driven by a fear that we have domesticated the entire planet – so “we desire to ingest pure wildness.” That is the psychological appeal of wild-fermented beers in an age of environmental crisis: they promise limitless abundance and diversity, and they position the drinker as a pioneer in an exciting new age of microbial exploration. “Break out from tired styles and taste the wild,” they beckon.

This narrative of wildness suffuses all microbiome research, casting the microverse as a kind of frontier space. It is prevalent in popular media, where articles abound with titles like “Gut Microbes: The New Frontier in Weight Loss” (Crowe 2017), “Are Microbes the Next Frontier?” (Wolfe 2014), and, in the “New Age of Exploration” issue of *National Geographic*, a “Small, Small World” (Bieri 2013). It characterizes biotech companies like MicroBiome Therapeutics, whose website features a page titled “A New Frontier.” And it certainly applies to academic researchers like Madden, who calls herself a microbe wrangler and microbial explorer, and recasts familiar places as wildernesses. “We know more about the microbes associated with deep sea trenches, tropical lichens, and the international space station than we do about the microbes associated with many of the arthropods that interact with our crops and live in our homes," her profile on the Rob Dunn Lab website reads.

This view of a relatively unexplored microverse is supported by metagenomics, which has revealed that we were far too limited in our early assumptions about the diversity of microbial life, because of The Great Plate Count Anomaly mentioned in Chapter Two. The degree of uncertainty regarding biodiversity is underscored by wildly differing total species number estimates, as E. O. Wilson emphasizes in his call to set aside half the planet for non-human life: "When expert estimates for invertebrates (such as the insects, crustaceans, and earthworms) are added to estimates for algae, fungi, mosses, and gymnosperms as well as for bacteria and other microorganisms, the total added up and then projected has varied wildly, from 5 million to more than 100 million species" (Wilson 2017).

In recent years cascading discoveries of new microorganisms have made biology's classic tree of life, a visualization based on Charles Darwin's metaphor for evolution in *On the Origin of Species* (1859), look increasingly outdated. Older trees of life (there is more than one model) focused on eukaryotes, organisms that have organelles in their cells, including a nucleus with genetic material. Eukaryotes are generally easy to describe, containing all visible life, from Cherrywood trees to Chihuahuas, to you and me. Yeasts are eukaryotes, too, but bacteria, which metagenomics has revealed to be earth's most abundant lifeform, are not. Mapping them onto the tree of life is messy, because of something called horizontal gene transfer (HGT), whereby bacteria swap DNA between individuals. "DNA flows so freely between them that the genome of a typical bacterium is marbled with genes that arrive from its peers," writes Ed Yong in *I Contain Multitudes*. "Even closely related strains might have substantial genetic differences"

(192). Archaea, recently discovered microorganisms which live in extreme, anaerobic places like hot springs, also sometimes engage in HGT (Fuchsman et al. 2017).

Undaunted, scientists have started to redraw the tree of life. In 2016, Jillian F. Banfield of the University of California, Berkeley and a team of colleagues diagrammed a new tree of life using a wealth of uncultivated microorganisms discovered through metagenomics testing, and some published genomes. It looks to me like a flower, or a feathered dinosaur, and contains "92 named bacterial phyla, 26 archaeal phyla and all five of the Eukaryotic supergroups" (Hug et al. 2016: 2).

There is a huge amount that we still don't know about those pterodactyl-like wings of bacteria, and the tail-feathers of archaea. But a world-wide hunt is on to uncover life in all of its invisible nooks and crannies. Microbiologists talk about the drive to map all biodiversity like settlers once talked about Manifest Destiny. They began in the 1990s by looking inside the human genome; widened the aperture slightly to study our symbionts in the Human Microbiome Project (https://hmpdacc.org/hmp/); crawled out of our skin and onto linoleum floors with the Home Microbiome Project (http://homemicrobiome.com); and now have set their moonshot goal with the Earth Microbiome Project (http://www.earthmicrobiome.org).

These Magellans of microbial exploration offer not only a vision of biological abundance – of discovering new species, rather than burying them in the graveyard of earth's sixth extinction – but also of unlimited economic potential. Madden's template for educating people about microbes isn't just about telling them romantic stories – how microbes make the flavors of chocolate cake, beautiful wines, your morning coffee – but is also about the untapped potential for microbes to make life better. "Most of the microbial world is the unseen diversity of life that exists on this planet," she says, "and with all of those species comes potential for applications."

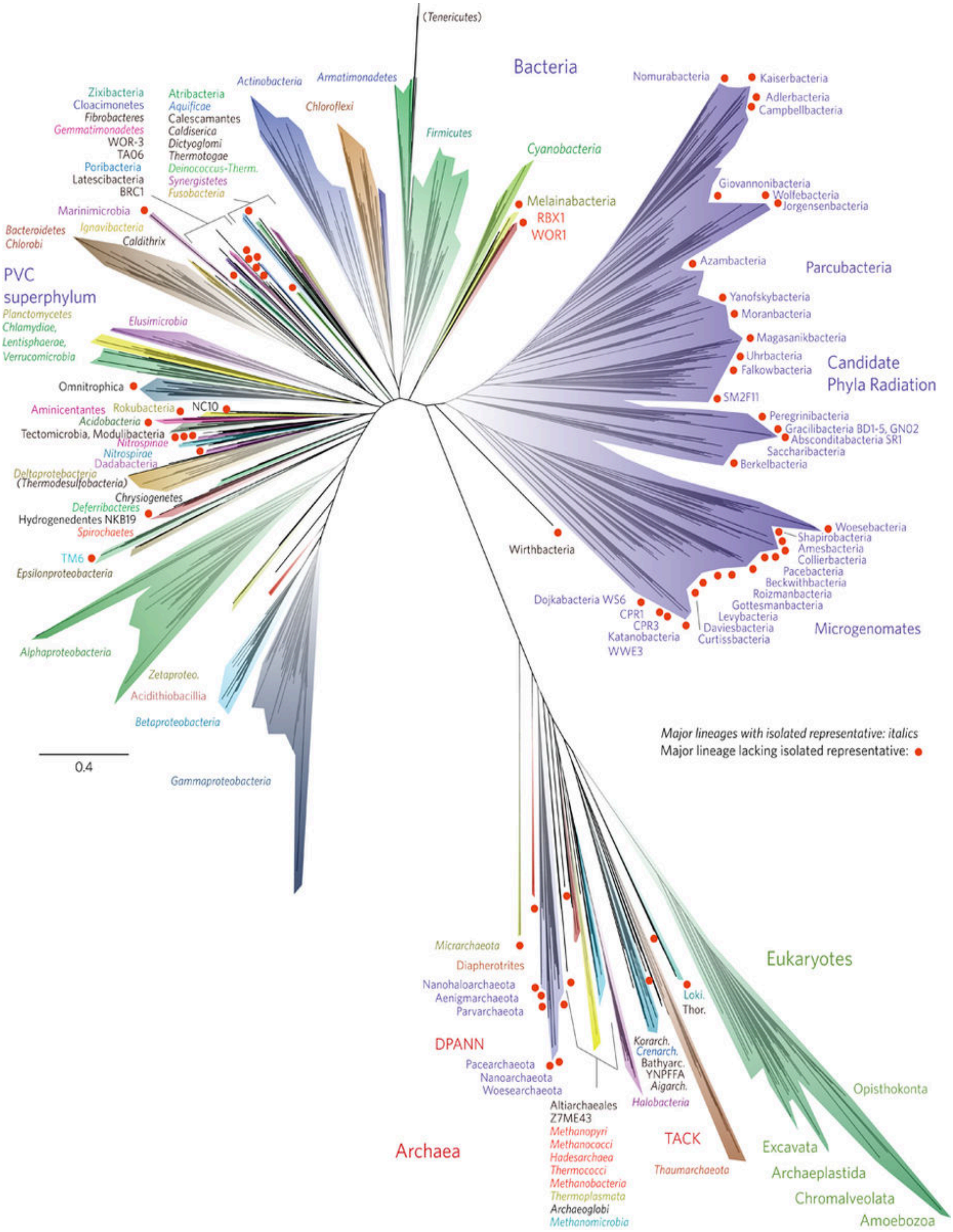

***Figure 8**: A current view of the tree of life, encompassing the total diversity represented by sequenced genomes. From "A new view of the tree of life,"* Nature *2016.*

The search for wild yeasts among craft brewers thus reflects in miniature a much wider quest to colonize the microverse to solve human problems (and make money doing so). This quest dates to the very beginning of the biotech revolution, in the 1980s. In *Life as Surplus* (2008), Melinda Cooper argues that the modern biotech industry was born out of the Reaganite, Neoliberal drive to overcome assumptions about the limits of economic growth and the perils of population growth. “At the height of the high tech euphoria of the 1990s, the biotech industry promised to overcome hunger, pollution, the loss of biodiversity, and waste in general, while the ecological and biopolitical problems associated with industrial capitalism only continued to worsen” (11). Today the solutions biotechnologists promise are just as lofty; the difference is that genomics is finally producing tangible results in an array of fields, from medical genetics, to sustainable agriculture, to craft beer.

In the last five years, for instance, money has flooded into agricultural biologicals, non-synthetic pesticides, herbicides, and fertilizers that use whole microorganisms, or compounds derived from them. Marrone Bio Innovations has four biopesticides on the market, and a patent on a bioherbicide that would be the first on the market. Biopesticides and bioherbicides are particularly interesting to Marrone’s organic farm customers, since they can be labeled organic (Guenther 2013). Monsanto, the largest seed company in the world, promotes a line of biologicals by helpfully noting on their website that “Microbes can be found in nature.” Given consumer and farmer resistance to their GMO seed lines, biologicals represent an opportunity to occupy the moral high ground.

(Interestingly, Monsanto’s website description for biologicals continues by outlining a list of fermented foods reliant on microbial activity: “Microbes have also been used in our food for thousands of years. From bread to cheese, yogurt, beer, wine, vinegar, soy sauce, sauerkraut, injera, kimchi, and even the preparation of chocolate.” Even the world’s largest agricultural conglomerate needs to borrow some gastronomic goodwill from time to time. Or perhaps especially.)

Agricultural companies face some of the same challenges as craft brewers in finding the right microbes and using them in the right way. A March 2016 *Wired* article compared microbe hunting to a giant fishing expedition: “With microbial strains, they’re fishing for something that works, but they rarely know why. And you can’t get to more targeted discovery without understanding biological mechanisms” (Zhang 2016). As of early 2018, Monsanto is testing some 2,000 bacteria for biopesticide applications, down from 18,000 in their initial screening. As with wild beer yeast strains, the narrative is that with grit and enough sifting, microbiologists will inevitably strike gold in the frontier microverse.

Of course, the sophisticated screening platforms that Monsanto and Marrone Bio Innovations use to find biologicals, that Madden used to find beer and bread yeasts, and that Afineur, a company we will meet in the next chapter, uses to find coffee bitterness-eating microbes, suggests a systems-based approach usually associated with mechanistic and engineering metaphors, not wildness. The paradox in the Anthropocene then is that we call things wild that we have already domesticated and changed; not only that, but we *know* we’ve changed them. We’re happy to carry on calling a beer “wild-fermented,” even when the brewing yeast was cultured in a lab and likely domesticated over the course of several brew cycles (in Alan Durstwitz’s terms, “trained for efficient wort fermentation”). Monsanto calls their biologicals natural, as if they just happened on a few insect-repelling soil microbes and bottled them up. But these microorganisms are commercial products that have been fundamentally changed in their transformation into “biologicals.” Monsanto’s “BioDirect™ Technology,” for instance, uses RNA Interference (RNAi) signaling to select for certain desirable traits in the microorganisms.

Perhaps I've drifted too far from wild yeasts, pondering what wildness means in the Anthropocene. John Holl, Senior Editor of *Craft Beer and Brewing Magazine* and co-host of the *Steal This Beer* podcast, thinks the evolution towards ostentatiously scientific brewing (including culturing wild yeasts) is simply a natural outcome of increased competition. It's the same argument Friedlander made in his series of blog posts about bioprospecting, but framed more in terms of the brewer's technical skill than the consumer's taste preferences. "Brewers recognize that if they want to grow, they have to have their science dialed in," says Holl. There are now more than 5300 breweries in the U.S. alone, up from less than 1500 a decade ago. Many head brewers have food microbiology or chemistry degrees from places like the University of California, Davis, Cornell University, and Oregon State University. "Taming" wild microbes is one way that breweries demonstrate that they are operating at the leading edge of fermentation science. "For us, it's what we do to make a better product," says Durstewitz of D9. "But to the consumers it's a differentiator that allows them to hear about us from a different perspective."

Chapter Four: Fermentation as Biotechnology

You might not think of coffee as being fermented, but it is. Around 1000 CE someone discovered that if the *Coffea* plant fruit, called cherries, were pulped they would ferment into an alcoholic beverage, similar to the Mayan discovery that cacao could be turned into alcoholic hot chocolate. In the thirteenth century people started roasting the fruit's seeds, or beans; the fermentation combined with the roasting unlocked complex flavors in the final beverage, while negating the alcohol. By the end of the thirteenth century the beverage was being called *Qahwah* in Yemen, which, *The Oxford Companion to Food* (2014) notes, was "originally a poetic name for wine" (205). This may reflect a connection drawn between wine's intoxicating and coffee's stimulating effect.

Coffee quality has dramatically improved in the last few decades, mainly due to closer relationships among coffee bean growers, traders, roasters, and retailers. Growing and harvesting techniques are more sophisticated, and the beans or beverage delivered to consumers are fresher. But the fermentation process remains haphazard.

Afineur, a Brooklyn-based startup, is focused on changing that. It was founded in 2014 by Camile Delebecque, a synthetic biologist, and Sophie Deterre, a flavor scientist. (Ben Wolfe was an early advisor.) Delebecque was an agronomical engineer by training, who quickly became captivated by the fermentation process. "I was curious, because it seemed that many fermented foods had not changed over thousands of years. I was wondering, with the various advances in biotechnology, if we could change food fermentation into a really controlled, tailored process to naturally make more nutritious, or easier, or more sustainable food products."

It seemed to Delebecque and Deterre that coffee was particularly stuck in a pre-microbiological age. "In a lot of countries, the pulp undergoes a natural fermentation," says

Delebecque. “People dump coffee cherries into water baths and let them rot. Sometimes it brings interesting flavor notes to the coffee beans, and sometimes less so. It’s less control, just whatever small microbes happen to be on the coffee cherry.”

Unruly fermentative processes are the norm not only at the commodity end of the production chain, but also at the luxury end. The most expensive coffee in the world, kopi luwak, or civet coffee, is the result of small mammals called Asian palm civets ingesting the coffee cherries and defecating them out in clumps, which farmers collect, separate out from other fecal matter, wash, and roast. The unusually low bitterness is due to cherries fermenting in the civet’s digestive tract. Civet coffee can go for $100–$600 per pound, and isn’t for everyone. A *Washington Post* review concluded “It tasted just like... Folgers. Stale. Lifeless. Petrified dinosaur droppings steeped in bathtub water. I couldn’t finish it” (Carman 2012). Animal welfare advocates object to kopi luwak for a different reason: civet farms in Southeast Asia are known to keep the animals in battery cages and force feed them coffee cherries.

Part of Afineur’s origin story is a visit Delebecque made to one such civet farm, after which he determined to improve the consistency and flavor of civet coffee, while eliminating the animal cruelty. *Nature Biotechnology* announced Afineur’s mission with the headline “Cat Poop Coffee Goes Biotech.” I asked Delebecque about these early reports, and he seemed slightly embarrassed. “It’s an anecdote that was amplified by the press early on. I did get curious about this project at the very beginning, but the mission was much broader.” That mission can be easily summarized: complete control over unruly fermentation. Spontaneous fermentation was the norm; now Afineur offers controlled fermentation.

Figure 9*: The Asian palm civet, a small mammal whose digestive processes ferment coffee cherries, sometimes under forced conditions. Credit: Evgeny Tchebotarev*

Cultured Coffee

Afineur's first product to market, called Cultured Coffee, makes a regular cup of joe feel quaint. Like coffee, but not the jitteriness and upset stomach you suffer after drinking it? Head to your nearest gourmet grocery store and track down Cultured Coffee. Or do as I did and order it from Amazon. Priced at $19.99, the five-ounce bottle of beans is about twice as expensive as my usual two-pound bag of whole French Roast beans, with about six and a half times fewer beans. Like kopi luwak, Cultured Coffee is clearly a luxury product.

But these are magic Arabica beans. They undergo a two-day controlled secondary fermentation by five microbes selected for their fondness for eating bitterness-causing enzymes found in the beans. "We can get microbes to produce more interesting compounds that are present in tea without losing any of the interesting taste," says Delebecque. The result is a low-acidity coffee that is also lower in caffeine.

One sunny March morning I brewed Afineur's magic beans. The packaging is exquisite. The bottle is small, but tasteful; the frosted glass might be on a bookshelf, filled with small seashells or smooth pebbles. The labeling is clean and modern, black type with red accents against a white background. The beans themselves are matte and dull brown, where my usual French Roast beans are shiny and darker; cracked and weathered, where my usual beans are laminate. Afineur's beans look slightly traumatized by the microbial tag-team.

I dumped about a third of the bottle into my grinder, mentally questioning the label's claim that it provides 10 to 15 servings. I like strong coffee, so my bean-to-water ratio is probably higher than average, but the two mugs of coffee I brewed using a third of the bottle was dispiriting. The aroma is faintly malty and delicate, the taste pleasant, smooth and light; some Amazon reviewers have described it as lemon-y. Afineur describes it as "fruit- and chocolate-forward," though I'm not quite getting the chocolate notes. All in all, an enjoyable coffee for people who don't like or can't easily digest strong coffee. But not for me.

Figure 10*: Cultured Coffee (light brown) vs. my usual French roast (dark brown)*

Figure 11*: A 5-oz bottle of Cultured Coffee costs about double a 2-lb bag of Safeway's French Roast.*

Building a Technology Platform

In a sense, fermentation was man's first biotechnology, our first application of a production process that manipulates living organisms to produce a useful good. Any crop you harvest or animal you kill naturally decays, acted on by enzymes or microorganisms already present in the plant or animal body, or by microorganisms in the air or soil. The raw materials of ancient diets (dairy, fruit, grains, meat) were either consumed quickly, became putrid, or fermented. The stuff that merely soured (milk) or sweetened (grains, fruits) was often tastier, safer to consume, and lasted longer than the raw materials from which it derived (Hutkins 2006: 3). This microbial manipulation occurred millennia before people knew microbes even existed.

Now that we know microbes exist, the abstract notion of fermentation as our first biotechnology has been replaced by a literal reality: fermentation is essential to the modern biotech industry. Its applications are extensive, in everything from sewage treatment, to ethanol fuel, to antibiotics and other pharmaceuticals. And, as this chapter shows, controlled fermentation is changing some traditional foods that once incorporated spontaneous fermentation, and even some foods that never had a fermentation step at all.

Afineur is a biotech company that happens to make specialty coffee — for now. "Our technology platform uses the latest advances in biotechnology and food science to transform fermentation into a process that is controllable and can be tailored to naturally improve specific characteristics of a food product," reads their website. Afineur's tools for doing so include using robotics to screen microbes, high throughput sequencing to rapidly map entire genomes, electron microscopy to analyze the structure of microorganisms, and techniques drawn from metabolomics, which describes what microbes are doing — what proteins they are producing and all of their metabolic reactions. "We are building a bridge between microbiome screening platforms and food science," says Delebecque. Other products will soon follow Cultured Coffee, including a plant-based protein powder that is made from recycled, fermented agricultural byproducts.

Afineur wears its biotechnological bent on its sleeve, making the microbe the centerpiece of their marketing campaign. “In microbes we trust,” reads their website (https://eatcultured.com). “Discover how we team up with microbes at eatCultured.com,” urges the Cultured Coffee bottle label. Delebecque is convinced that the public is ready to embrace an overtly scientific marketing message about fermentation, in part because it already has. Rather than accept venture capital money, Delebecque and Deterre’s Kickstarter campaign quickly raised $51,000 across 894 first orders (Delebecque 2015). “I think there has been a radical switch in how people are perceiving microbes in the last few years, with more chatter around microbiomes, and the rise of other fermented products like Kombucha,” says Delebecque.

Therein lies the secret ingredient to Cultured Coffee’s success, as for many other fermented food products today: health claims.

When in Doubt, Call it a Probiotic

Cultured Coffee began life as a specialty, better-than-kopi-luwak coffee. Delebecque may find the kopi luwak media narrative overplayed, but Afineur’s Kickstarter page promoted Cultured Coffee as going “Beyond Kopi Luwak: a cruelty-free and sustainable fermented coffee”; there was also a helpful “Cultured Coffee vs. Kopi Luwak” comparison in the FAQ section. It ends, “By controlling and fine-tuning the fermentations which are done in clean and safe bioreactors we are able to uncover unique exceptional flavor landscapes that go well beyond anything kopi luwak can offer. An incredible cup and a truly high-end experience for a fraction of the price.”

So it is fair to say that Cultured Coffee was originally marketed for its taste and perhaps its kindness to civets. Yet Afineur pivoted, scrubbing the kopi luwak mentions from their website, and marketing Culture Coffee primarily as a specialty health product. Afineur's website emphasizes that their coffee is easier to digest ("lower in acidity and stomach irritants") and provides more sustainable energy ("bioactive compounds and lower caffeine"). The Cultured Coffee label, and the copy on their Amazon product page, are likewise about health first and taste second. The kicker for me is the line "coffee turned superfood through natural fermentation."

Figure 12*: The Cultured Coffee label reveals a focus on health claims.*

The term that Julia Child used to describe such reductive health marketing is "nutritionism." Like food writer Michael Pollan, she promoted eating "real food," meaning unprocessed or minimally processed foods that do not require a nutrition label. In Pollan's haiku-like formula, "Eat food. Not too much. Mostly plants" (Pollan 2007).

But selling fruits, vegetables, and other agricultural staples is not especially profitable for manufacturers (or for that matter, grocery stores), and so, in the 1980s, they started selling "nutrients" instead. Pollan (2007) described this transformation for the *New York Times*:

> Where once the familiar names of recognizable comestibles – things like eggs or breakfast cereal or cookies – claimed pride of place on the brightly colored packages crowding the aisles, now new terms like "fiber" and "cholesterol" and "saturated fat" rose to large-type prominence. More important than mere foods, the presence or absence of these invisible substances was now generally believed to confer health benefits on their eaters. Foods by comparison were coarse, old-fashioned and decidedly unscientific things – who could say what was in them, really?

The essential claim of nutritionism is that foods can be engineered for greater health. That is the underlying premise of Cultured Coffee: that science improves coffee's healthfulness.

What has changed as biotechnology advanced is the mechanism of nutritional improvement: instead of pumping vitamins, fiber, and minerals into maximally processed foods – a practice consumers are increasingly aware is putting lipstick on a pig – Cultured Coffee uses a fermentation step to biologically change the coffee bean microbiome. Since fermentation is used in most coffee production already, it doesn't bother consumers. But nevertheless it is a processing step that allows Afineur to charge a stratospheric price for one of the world's oldest beverages.

Afineur is not alone in marketing a health-boosting fermentation step. RFI Ingredients, for example, sells a line of "FermaPro" ingredients that undergo a proprietary fermentation process. "Many regular foods become even healthier when fermented, due to improvement in bioavailability of nutrients and phytochemicals, elimination of anti-nutrients or the increased production or creation of phytonutrients found in the raw material," their website reads. The FermaPro Black Garlic claims improved "immune-supportive activity and antioxidant potency—doubling the oxygen radical absorption capacity."

This "fermentation nutritionism" speaks to the growing popularity of probiotics, a Greek words that literally means "promoting life." In a sense they are anti-antibiotics, dense concentrations of live microorganisms that are meant to correct imbalances in your gut microbiota through addition rather than subtraction. In 2012, 3.9 million Americans consumed probiotics, four times higher than in 2007 (Clake et al. 2015: 5). Ed Yong (2016) is supportive of the concept, but not its current execution. "Even the most concentrated probiotics contain just a few hundred billion bacteria per sachet. That sounds like a lot but the gut already holds at least a hundredfold more. Gulping down a yoghurt is like ingesting scarcity. Rarity, too: the bacteria in these products are not important members of the adult gut" (222).

The popularity of prebiotic and probiotic supplements, and probiotic health claims on traditional fermented foods like yogurt and Kombucha, highlights growing public awareness that gut microbiome health matters to overall health. Doctors now speak to patients with gastrointestinal disorders like Crohn's disease about keeping their microflora "in balance." In extreme cases they prescribe fecal transplants, the undeniably gross but equally undeniably effective practice of transplanting a healthy person's stool into a sick person's colon to help reset their gut microbiome. An avalanche of studies finding linkages between our gut microbiome and a wide range of diseases and disorders are reported in popular media, from obesity (John and Mullin 2016), to multiple sclerosis (Guglielmi 2017), to autism (Li et al. 2017). Many of the studies are preliminary and lack evidence of causation, but the takeaway for readers is clear: they should worry about their gut microbiomes. And, by extension, they should consume foods with probiotic qualities. Industrial manufacturers have caught on, offering probiotic product lines. Dannon's probiotic Activia yogurts helped the company leapfrog General Mills as the largest yogurt manufacturer in the world in 2013 (Schultz 2013).

If it seems like I'm being dismissive of health claims about fermented foods, I don't mean to be. There are very few randomized, controlled clinical studies regarding the probiotic effects of fermented foods. But although probiotics lack scientific evidence supporting their health claims, there is more general evidence that fermented foods do confer health benefits "not directly attributable to the starting food materials" (Marco et al. 2017). Cohort studies of populations whose diets are rich in traditional fermented foods like kimchi or kefir show greater average lifespans and associated health benefits than populations whose diets do not incorporate traditional fermented foods.

What I object to more is the way fermentation is cleaved from fermentation traditions in the food biotech realm. With Afineur, RFI Ingredients, and other biotech companies that market an added fermentation step, it's a formula: food + fermentation = health. The cultural import of fermentation traditions developed over thousands of years is replaced by a product-agnostic fermentation technology platform. The economic value of whatever that product is increases, since, as the MIT anthropologist Ben Wurgaft told me, "the product of intellectual life in Cambridge or Palo Alto allows you to charge more." But that increase in value does not necessarily support a system of agricultural production. Cultured Coffee has no sense of place. The most important ingredient — the bean — is described in Afineur's literature as simply "green Arabica beans." From where? Who is growing them? Using what methods? The identities of the growers and their beans seem beside the point.

Cultured Coffee is "smart," certainly, and it may be healthy for people who suffer indigestion. But is it "cultured," except in the strictly biological sense of growing something in an artificial medium?

Artisanship and Technology

I certainly don't mean to be overly negative on Afineur – their manipulation of the coffee microbiome is impressive – but one thing nags at me: their name and their approach to food production do not match. "Afinage" is the French word for "cheese maturation" the process of ensuring that a cheese develops into the best version of itself, sold at the perfect moment of ripeness. (An afineur is the person overseeing the afinage.) France has used cheese caves to help control environmental variables during the cheese aging process for centuries, and the concept has caught on in most major cheese-consuming or producing nations. In the U.S., it is common for high-end cheese shops to buy young cheeses and to age them in purpose-built subterranean vaults, bringing them up to the cheese counter only at peak maturity. Murray's Cheese Shop in New York City, for example, has a line of their own cave-aged cheeses.

In exerting so much effort in the specialized care of individual cheeses, afinage has become a proxy for quality in the cheese industry, and an extension of artisan production processes. Nobody cave-ages Kraft Singles. Afinage is the back end of a long process of "raising up" the raw milk – which, like an infant, is full of potential but has not yet revealed its character – into mature and flavorful cheese. As Bronwen Percival writes, "Cheese is not so much milk's leap toward immortality as its passage to adulthood" (Percival 2017: 17). The young milk is imbued with complex microbiological communities derived from farming, animal bedding and feeding, milking, breeding, and other husbandry practices, as we will learn in Chapter Five. Artisan cheesemaking is about expressing that microbiological potential through fermentation and controlled aging, which afinage finishes. Afineur's fermentation technology platform though is about microbial intervention, rather than expression.

Delebecque seems aware that Afineur is threading the needle in terms of promoting a vision of scientific progressivism, based on a fermentation technology platform, while staking a claim to artisanship. Their emphasis on the “naturalness” of their bitterness-eating microbes, for instance, seems to be about banishing the perception that Afineur is using the most controversial of microbial interventions, genetically modified organisms. Delebecque’s doctoral work involved genetic engineering. “I don’t have a strong revulsion to those types of tools,” he says. “I just think they are not necessary for now to what we are trying to achieve.” In the current consumer climate, it is a lot safer to promote designer microbiomes than designer (GMO) microbes.

Other fermentation-reliant biotech food companies though have come closer to embracing GMOs. Geltor, Clara Foods, and Perfect Day are all food tech startups that use genetically modified yeasts to ferment new products (Kowitt 2017). Geltor makes animal-like textured materials that are vegan, such as animal-free gelatin, traditionally derived from collagen (cow or pig bones, skin, and tissues). Clara Foods makes chicken-free egg yolks, and Perfect Day makes cow-free dairy proteins. The catch is that while the yeasts are genetically modified, what they produce is acellular. Since the yeasts are removed from the products, they don’t need to be labelled GMO (Kowitt 2017).

Whether or not the yeasts or bacteria are genetically modified, the takeaway is that biotech food startups have figured out how to turn microbes into factories for a wide array of products, from coffee beans, to gelatin, to eggless egg whites. There is no workmanship of risk when Afineur’s team of microbes go to work reducing the acidity of green coffee beans, or when Perfect Day’s genetically modified yeasts convert sugars into dairy proteins. Yet in both of these cases, and in marketing materials I have found for other fermentation-focused food biotechs, there are claims to artisanship. Perfect Day, for instance, explains on their website that “Instead of having cows do all the work, we’ve developed a process similar to craft brewing.” Afineur just happens to be more blatant than most about it, putting their claim to artisanship in the company name.

Can a producer embrace the promise of modern microbiology without losing the traditional practices and workmanship of risk that defines fermented food artisanship? Can the lab and the farm coexist? On a cold February weekend, I drove five and a half hours from Westchester, New York, to Greensboro, Vermont, in search of an answer.

Chapter Five: American Terroir

***Figure 13**: Jasper Hill Farm when I visited in February. Mateo's house is attached to the barn, with a creamery in the basement where they make Bayley Hazen.*

Brothers Andy and Mateo Kehler founded Jasper Hill Farm in 2003 with a mission: to build a model of agricultural entrepreneurship that might revive the fortunes of dairy farmers in the Northeast Kingdom of Vermont, the heavily forested northeast corner of the state. At the time the Kehler brothers founded Jasper Hill, farmers were in a decades-long decline due to the unsustainably low price of milk. Vermont dairy simply could not keep up with the flood of California milk produced on mega-farms. Fifty Vermont dairy farms had shuttered the year before, and Andy and Mateo, college-educated and politically committed to sustainable agriculture, figured that artisan cheese, not fluid milk, was the only hope for Vermont's dairy farmers. "From the beginning, [Mateo and Andy's] plan was to help develop the local economy in a way that would compromise neither what they described as the 'culture of independence' of Vermont's people nor the 'working landscape,'" writes Heather Paxson, an MIT anthropologist whose book *The Life of Cheese* (2013) casts the Kehlers as the face of a new generation of cheese artisans (2).

Vermont dairies continue to struggle, but Jasper Hill has succeeded to an astonishing degree in providing a model for agricultural entrepreneurship. Last year Jasper Hill crossed $100 million in lifetime sales. Mateo and Andy, who began by making cheese with their wife and fiancé, respectively, now employ about eighty people. More than the financials, though, is the sense of pride that Vermonters feel having perhaps the best cheesemaker in America. In 2014, when President Obama hosted French President Francois Hollande for a state dinner, he served the leader of the greatest cheese culture on earth Bayley Hazen Blue, Jasper Hill's raw cow's milk blue cheese. In 2017, Jasper Hill's line of smear-ripened soft cheeses swept the category at the U.S. Cheese Championship (the largest U.S. cheese competition), winning first through fourth place. Harbison, a bark-wrapped bloomy rind cheese, was named the best cheese in America.

Despite the growth in employees, revenue, and quantity of cheese sold, Jasper Hill makes a reasonable claim to remaining a family affair. Andy lives just down the street from Jasper Hill, and Mateo lives on top of it; his loft home, connected to a barn with about fifty dairy cows, is above one of Jasper Hill's two creameries. (The other is at the Vermont Food Venture Center, a shared hub for food businesses.) Mateo's son, who is in eighth grade, goes there every evening after soccer practice and flips Bayley Hazen molds, allowing gravity to evenly wring out moisture. He's paid $10 per hour for the chore; it used to be $7, but last year he got a raise. "Part of what I'm teaching him is how to value his time, and how to negotiate in business" says Mateo.

Jasper Hill's production practices have also remained largely traditional — the curd is cut, the whey drained, and the curds molded (or "hooped") all by hand. But to an unusual degree, Mateo and Andy have used the latest scientific research to innovate on traditional cheesemaking practices. For instance, Jasper Hill's cheese aging facilities, collectively called The Cellars, are modernized versions of French cheese caves. They consist of seven vaults deep inside a hill near the creamery, which took ten weeks to blast. The walls are made of thick concrete, and a sophisticated climate control system, which tweaks humidity, temperature, and oxygen and CO_2 levels, ensures that each vault is optimized to mature a different cheese family. *Penicillium roqueforti*, the mold that forms those blue streaks, blooms in the presence of abundant oxygen, so in the Bayley Hazen vault there's a lot of air exchange. "We are pulling out the ammonia and CO_2, and pumping oxygen back in," says Mateo. Vaults that house soft and bloomy rind cheeses, like Winnimere and Harbison, are warmer and more humid.

This is affinage in action, not words.

When I toured the vault where Jasper Hill ages Alpha Tomen, an alpine-style raw cow milk cheese, I was surprised to see a robot blocking one aisle (Jasper Hill Farm 2017). It looked like the elevator Charlie and Grandpa Joe blast off in at the end of Willy Wonka, a tall cylinder made from Plexiglas and steel. The robot moved efficiently down a row of wooden shelves, searching out cheese wheels with a laser and pulling them out with a paddle-arm, like a pizza maker's peel. It placed each wheel on a stainless-steel washing station, washed it with a brine solution to encourage microbial growth, flipped it over, sprayed it again, and placed it back on the shelf. The robot also has a vacuum apparatus to hoover up the tiny mites that are fond of Cheddar cheeses, eliminating the Sisyphean task of brushing them off by hand. Mateo adds that Jasper Hill is "not really in the business of wearing people's bodies out," and adds that this is the first robot of its kind in North America, though others like it are already being used in Europe to age hard cheeses like Comte and Gruyer.

Figure 14*: Mateo and an intern named Vicente in vault three, where Bayley Hazen wheels are matured.*

Vacuuming cheese mites and washing and rotating hundreds of wheels of Alpha Tomen daily with a brine solution is backbreaking work when done by hand, so there is an obvious efficiency and manpower benefit to using a robot. But even this technological marvel honors a traditional cheesemaking practice. The robot has a storage tank that collects the runoff from those washings; this concoction of whey, brine, and cheese scraps is called morge, and developed in France, where it gives Beaufort cheese its characteristic russet-colored rind (“Beaufort Chalet [Alpage]”). “This is an incredibly rich microbial soup,” says Mateo. “It’s thick, viscous. It is biofilm that’s being peeled off and hydrated and collected as the cheese is getting washed.” Morge is known to contain over 480 species of bacteria, a complex microbiological community that Mateo compares to a sourdough mother, and which, having smelled it out of the food-grade plastic bin it is stored in, I’ll compare to the worst high school gym locker you can imagine.

What Jasper Hill has done is to introduce a practice of microbial transference, whereby younger, soft cheeses are washed with morge developed from older, hard cheeses. “You are just inoculating with hundreds of millions, billions of microbes,” says Mateo. Using the morge has reduced the rind formation time on Jasper Hill’s soft cheeses by about a month. But Mateo says that is not the main advantage: “Reducing aging time is one thing, but actually developing a consistent healthy rind, and also developing a wash solution that is endemic and specific to this place and this cheese, is another.”

Jasper Hill’s efforts to modernize the cheesemaking and aging process usually have a similar basis in the microbiology of traditional cheesemaking practices. Mateo is fascinated by cheese microbiome research. I witnessed this when I worked with him on *The Oxford Companion to Cheese*, when I was an editor at Oxford University Press and Mateo a member of the *Companion*’s Advisory Board. He recruited a network of scientists to contribute entries, including his “intellectual crush,” the French microbiologist Marie Christine Montel. (Montel developed the relative index we learned about in Chapter Two.) In his Foreword to the *Companion*, Mateo wrote that “The recent advent of molecular biology, whole-genome sequencing technologies, and microbiome research makes this an incredibly exciting time to be a cheesemaker” (vii).

Jasper Hill’s formal collaboration with academics and scientists began in 2010, when Rachel Dutton, the Harvard microbiologist who sequenced Jim Lahey’s sourdough starter, and her postdoc Ben Wolfe had an intuition that cheese rinds would be a perfect medium for learning about microbial ecosystems. It was Mateo who then taught them how to make cheese, and introduced them to cheesemakers; soon Dutton and Wolfe had 140 cheese samples from all over the country. Bayley Hazen Blue was one of the first cheeses that Dutton put under the microscope; Mateo says Rachel and Ben sequenced thousands of samples of the microbial communities of Bayley over six or eight months.

Mateo found their analysis so fascinating that he had Jasper Hill build its own lab, which was ready in 2013. It's more modest, and much messier than I expected. I saw two rooms, filled with standard lab equipment: a wall of beakers and flasks and funnels hanging from rods set at a 45-degree upwards tilt to drain, petri dishes, staining glass, etc. But among the clutter was advanced equipment. Panos Lekkas, a large and garrulous Greek who is the head of Quality Assurance — really, he's the chief scientist — gave me a rundown of his favorite toys. "We have a thermal cycler, which is something to amplify your DNA, it raises temperatures up and down very fast. We have the hood, that is required for everything. We've got incubators, enough of them to actually grow at different temperatures and different environments, which we use a lot. We have gel apparatuses and UV lights. And then lately, we are upgrading to more technical equipment, like a quantitative PCR. That will allow us to track the growth of organisms throughout the lifecycle of the cheese."

As a result of their lab research and ongoing collaboration with Dutton (now at UC-San Diego), Jasper Hill no longer uses commercial starter cultures. Starter cultures are bundles of microorganisms (usually lactic acid bacteria) that kickstart the curdling process. Like beer yeasts, these starter cultures have been developed to work extremely well in the production of large-batch industrial cheesemaking, where consistency, high yields, and low costs are the primary considerations. But they are not ideal for artisan cheesemakers operating on a smaller scale. “The very elements that make starters suitable for factory production – such as turbocharged acidification – present technical challenges for cheesemakers working on a different scale,” writes Percival (159). Besides technical challenges, some artisan cheesemakers – Jasper Hill very much included – are loathe to purchase cultures from agrochemical corporations whose ethos they interpret as antithetical to their own. The cheese culture industry – again like the beer yeast industry – has undergone a deep consolidation in recent years, and the few players that remain tend to be large conglomerates. “Dupont, Cargill, and CH Hansen. They own everything,” says Mateo.

The Jasper Hill-Dutton research collaboration showed commercial starter cultures were being quickly outcompeted by the lactic acid bacteria native to the milk, allowing Jasper Hill to eliminate all starter cultures from their raw milk cheeses a few years ago. But since pasteurization kills off the lactic acid bacteria in milk, Jasper Hill’s pasteurized cheeses still need help to curdle. Their solution was to brine-wash or morge-wash many of their cheeses, which bring in microbes on the salt molecules and in the morge biofilm. Jasper Hill is also experimenting with starter cultures derived from Jasper Hill’s own farm, creameries, or cellars. “We have a bank of about 1000 microorganisms here that are sometimes the same microorganism but different isolates, so now we are taking our starter cultures and seeing who grows better with whom. And that is a huge project,” says Lekkas. Once Jasper Hill gets a handle on what groupings of microorganisms do best to culture which families of cheeses, Lekkas hopes to help other cheesemakers develop cultures native to their farms or creameries. “We want to give the people the option to choose. Right now they do not have the option.” (Commercial ripening cultures, which help with the cheese development after initial fermentation, are still used selectively in both Jasper Hill's raw and pasteurized cheeses.)

Figure 16*: The two-room lab at Jasper Hill Farm packs a lot of equipment into a small space.*

Figure 15*: Incubators on the left, and a standard fume hood on the right.*

More impressive perhaps than the lab itself is the fact that it exists at all. Unlike the craft beer industry, where yeast research labs are still uncommon but not unheard of, I am unaware of any other artisan cheesemaker in the U.S. that has such a facility. Mateo does not envision that will change soon. "We're doing this because we're just curious, not because it is ever going to make us any money. [It's] because we want to learn and we want to be relevant and ahead of the science and be right there with it — to understand the fundamentals of the products that we are producing, and the practices that are producing the microbiology that underpin our products."

In large measure, Jasper Hill's lab exists to help quantify and perfect the terroir of their cheeses. The company's motto, "A Taste of Place," happens to be cultural anthropologist Amy Trubek's very definition of terroir (Trubek, Guy, and Bowen 2010). Terroir describes the sum total of the decisions that a cheesemaker (or any food artisan) makes, which cumulatively produce a product tied to a distinct place. It is importantly distinct from craft breweries' pursuit of wild yeasts and other microbes. Jasper Hill is not necessarily searching for uncommon or unique microbes, but the right ones, in the right proportions, to produce a characteristically Vermont clothbound cheddar.

Every decision along the way matters. Studies have shown, for instance, that cow teat skin is a major reservoir of microbial diversity that makes its way into milk. The cow teat microbiota, in turn, are determined in large measure by the forage fed to the cows (grazed grass, hay, or silage), the breed of cattle (or sheep or goat, though Jasper Hill mainly works with cow's milk from their own Ayrshire herd and from local farms), and the conditions in which the cows are stalled (Frétin et al. 2018). It is an interconnected system of farming, dairying, and cheese aging that, at a microbiological level, determines the final product. "The way that we feed our cows, the way we bed our cows, our milking protocols, the way we clean our equipment, are all intended to steer and create selective pressures on the microbial ecology that ends up in that milk," says Mateo. This is what he means when he talks about the "practices that produce the microbiology."

Defining Terroir

Terroir first emerged in France in negative usage, to describe products or even dialects that were provincial: "Until the early twentieth century, wine and viticultural experts scorned wines with a perceptible terroir for being unrefined rustic *plonc,* not fit for refined urban palates that esteemed ‘noble’ wines from higher-status producers that managed to transcend the soil” (Rogers 2016: 706). With the integration of the European Union in the mid-twentieth century, individual countries felt a need to defend their food and beverage traditions against foreign imitations. There was also concern about cheap factory knock-offs flooding the market, domestically and internationally. Marks of distinction for food proliferated in Europe and were eventually consolidated under three labels: PDO (protected denomination of origin); PGI (protected geographical indication); and TSG (traditional specialty guaranteed). Today, all but TSG specify a geographical boundary outside of which a product cannot legally be made.

In Europe, terroir underpinned a protectionist economic system. It idealized the hand-crafted products of centuries of European peasant labor and protected small artisan traditional food producers from global competition. But the U.S. does not have a long history of artisan cheesemaking. Actually, we don’t have a long history, period. Seventeenth-century Colonial Puritans did engage in commercial cheesemaking in New England and even exported their hard cheddar-style cheeses to the West Indies, as Paul Kindstedt describes in *American Farmstead Cheese* (2005):

> Before immigrating to New England, these Puritan dairy farmers had been schooled in the agricultural concept of competency, with its emphasis on near self-sufficiency, combined with the efficient production of products for external sale… In short, they knew how to produce cheese for export and they understood that there was money to be made by doing so, provided that they had access to a stable and profitable market. (20)

But commercial cheesemaking from 1650 on was essentially limited to the English hard cheeses. (There was some soft farmstead-style cheese produced by Puritan wives, but these were only for domestic consumption.) Cheesemaking in Vermont has an even shorter history of about two hundred years; it revolved around one style for most of that time. According to Kindstedt, commercial cheesemaking in Vermont tracked the northward migration of southern New

Englanders following the Revolutionary War, and, as with Puritan production, centered almost entirely on English-style cheddars.

It wasn't until waves of immigrants from across Europe arrived in the mid-nineteenth century that new cheese styles emerged in the U.S. But even this spike in small-scale cheese production dissipated quickly, coinciding with the first American factory production of cheeses. Jesse Williams, a Connecticut farmer's son, figured out that if he specialized in cheesemaking and left dairying and wheat farming to others, he could produce a more consistent and higher-quality product. He opened his cheese factory in Rome, upstate New York, in 1851. By 1865, there were 500 more cheese factories in the U.S. (Bradley 2014).

Today, nearly all American cheese styles are interpretations of European classics. Alpha Tomen, for instance, is Jasper Hill's take on Appenzeller, an alpine Swiss cheese. Cabot Clothbound reimagines the British clothbound cheddar, bound in muslin or cheesecloth and brushed with lard, originally from Somerset, England. Bayley Hazen Blue is a denser version of the classic English natural-rind Stilton.

This is not a knock on Jasper Hill, which has reinterpreted European classics in endlessly creative and delicious ways. It is simply to state the obvious, that as a young nation formed from European immigrants, we do not have many "American original" cheese styles, nor even a long history of reinventing classic European styles. This appropriation of European styles is not remotely cheese-specific. *Prosit: A Book of Toasts* (1904) includes this drinking poem:

> *A Frenchman drinks his native wine,*
> *A German drinks his beer;*
> *An Englishman his 'alf and 'alf,*
> *Because it brings good cheer;*
> *The Scotchman drinks his whisky straight,*
> *Because it brings on dizziness;*
> *An American has no choice at all,—*
> *He drinks the whole damned business.* (4)

If terroir depends on a product's long history of production, tied to a specific place, then it is difficult for American cheesemakers – or, for that matter, beer, spirits, or wine makers – to claim the European concept for their own.

Perhaps though American cheesemakers can simply appropriate and reinvent the concept for our own, as we have so many other foreign influences. Paxson makes that argument in a fascinating article titled "Locating Value in Artisan Cheese: Reverse Engineering Terroir for New-World Landscapes" (2014). In it, she writes that:

> …terroir is being reframed as a prescriptive category for thoughtful action, for bringing-into-being from the ground up places where some wish to live and others want to visit. For these rural entrepreneurs, terroir is not an a priori quality to be discovered through selective recuperation of the past; rather, it is something to do to make the future. (445)

According to this thinking, Jasper Hill is reverse-engineering terroir by promoting certain qualities of Vermont's rural agricultural landscape, such as the independent family dairy farmers Jasper Hill buys milk from, and the Vermont grasslands their cattle are seasonally pastured on, in order to create market demand for Vermont- and even Northeast Kingdom-specific cheese. That demand in turn supports "rural entrepreneurs, ecological stewards, sustainable developers, local citizens, and conscientious dairy farmers" who have the capacity to transform Vermont into the very agrarian working landscape Old World terroir idealizes. Instead of defending a pre-existing culture of artisanal food production, this American terroir is an aspirational attempt to help a culture of artisanal food production take hold. "Representing a critical response to the deterritorializing effects of commodity pricing that has led to the collapse of small farms and their consolidation into huge, industrial dairies," Paxson writes, "artisan cheesemakers invest their productive activity with potential not only to express place through taste but also to create place" (451).

This is a beautiful notion, but messy in practice. A new American terroir has not been codified or standardized in any meaningful sense. Individual producers promote the “terroir” of their products without agreeing to what terroir means. Sometimes this works out fine; consumers are clear that Napa Valley pinots are distinct from Willamette Valley pinots. But other times a fuzziness creeps in, and terroir becomes little more than marketing-speak.

One reason bioprospecting is so appealing for breweries is that brewing with “native” or “indigenous” yeasts allows them to claim a kind of microbial terroir. That is the gist of Wisconsinite, the beer brewed by Lakefront Brewery that features “a unique, first-of-its-kind, never before fermented, indigenous Wisconsin yeast strain.” The narrative here is silly – I’m not sure yeasts recognize state boundaries – but it’s propagated uncritically by the media. An NPR article on bioprospecting for sour beers, for instance, concludes “Put simply, microbes are the new terroir — one that, thanks to sour beer, tells a more educational story than the same old *Saccharomyces* tale” (Graber-Stiehl 2017).

The appeal of microbial terroir is not limited to breweries; famous chefs and restauranteurs, too, are enamored of the concept. David Chang, of Momofuku and *Ugly Delicious* fame, is one of three authors on an article published in the *International Journal of Gastronomy and Food Science* (2012) titled “Defining microbial terroir: The use of native fungus for the study of traditional fermentative processes.” The paper describes a fungi found growing on *butabushi* – Momofuku’s pork take on *katsuobushi*, a dried, smoked, fermented bonito snack popular in Japan – and the discovery that the strain was native to Momofuku’s culinary lab. The paper’s abstract effuses, “As a chef one not only has the chance to understand their craft on a cellular level, but to connect more deeply to the indigenous life of their environment, their ‘microbial terroir’” (64).

Contract labs have also promoted the concept as a rational for their analytical services. Agro BioServices Inc. even trademarked the term: Microbial Terroir™ "explores the total community of microorganisms that shape our food" and promises to "alter this microbial landscape, encouraging positive traits and eliminating those that negatively impact your product." When Arm & Hammer's parent company bought Agro BioServices in 2017, they had some fun with employee cluelessness about how to pronounce "terroir," posting a YouTube video featuring about two dozen people butchering the term (Arm and Hammer Animal Nutrition 2017). My favorite is the guy who managed to also mispronounce "microbial" as "micro-bial."

Scientifically, microbial terroir is on unproven ground. The Dutch microbiologist Lourens Baas-Becking is credited with the Baas-Becking hypothesis of microbes, which states that "everything is everywhere, but the environment selects." I've heard it summed up simply as the "everything and everywhereness of microbes," meaning that you can find the same species of microbes in astonishingly varied and far-flung places. In fermentation, it means that the general recipe and fermentation environment determines the microorganisms that thrive. Remember, Jim Lahey's sourdough starter featured a lactic acid bacterium (*Lactobacillus sanfranciscensis*) that can be found in sourdough starters globally, despite being cultured from a cabbage leaf in Italy. Research from Dutton's lab on cheese rind microbial communities similarly found that the style of cheese – mainly its moisture content – selects for the dominant microorganisms, rather than the reverse (Wolfe et al. 2014). In *Reinventing the Wheel*, Percival writes about the disappointment of that finding: "The tacit hope had been that Dutton and Wolfe's high-tech tools would demonstrate the uniqueness of each cheesy snowflake. Instead, the experiment showed that similar and predictable communities assemble on cheeses of the same style, whether they are in California, Somerset, or the Pyrenees" (170).

Nevertheless, the hypothesis that certain microbes are endemic to certain places is a powerful one. Research in the 1990s on different strains of lactic acid bacteria found in milk from farms in Normandy showed preliminary evidence that the strains were in different families from one another, and that some of those families weren't even related to reference strains (Corroler et al. 1998). Wolfe is now researching soil microbiology and the transfer of microbes from the soil into fermented foods made from plants, hoping to show that the microbial composition of, say, kimchi, is influenced by the soil in which the cabbage was grown.

Perhaps then microbial nativity exists to some degree. But even strain variation in microbes does not necessarily add up to "terroir." Anne Madden described to me how the same yeast strain will behave quite differently depending on what it is feeding on, the temperature it grows at, and other environmental variables. "Brewers know this because if they get the temperature wrong and they start to stress that yeast out, it's going to start producing diacetyl, compounds that taste like butterscotch." Decisions that brewers make, and that indeed all fermented food artisans make, regarding the environmental conditions of the fermentation change the behavior of the microorganisms, and arguably have a larger impact on the final product than strain or species differences in the ferment.

But the biggest problem with microbial terroir is that it focuses inordinately on the role of a few microbes in the fermentation process, when fermentation is really about the interactions among all different species in a community. It is close to boasting "I have the best microbes," when you should be saying "I have the best microbiome." Next to the scale of Jasper Hill's endeavors to create a system of terroir for cheese made in the Northeast Kingdom, claiming you can achieve it by capturing individual microbes feels simplistic, a sentiment Lekkas shared:

> The natural microorganisms are going to give you a much greater flavor profile, much more robust. If that's what you think terroir is, then good, you've done it. But we have

> kind of taken one thing that we can do and made it the only thing. I struggle to find a single thing in life that isn't a system. I do not think we should only say oh, microbes, they are the best. It's a piece in a puzzle.

Unfortunately for Americans, the one practice that most impedes the creation of terroir in cheese is also the practice that regulators love best: pasteurization.

Obliterating Terroir

In Europe and much of the rest of the world, raw milk cheeses are beloved and protected with trade designations that do not allow their production outside a traditional production zone, such as the Protected Designation of Origin (PDO). PDO Salers, a semi-hard raw milk cheese, can only be made from the milk of the Salers cow breed, by a farmer in the Cantal mountains of the Auvergne (France). But in the U.S. raw milk cheese is banned unless it is held for 60 days before sale. The law dates to World War II, when the government ordered massive quantities of cheese for troop rations and outbreaks spiked. Cheesemaking facilities at the time were not built for that production scale, and many of the knowledgeable cheesemakers were overseas fighting, leaving behind overmatched apprentices (Hay 2018). A sixty day holding period in refrigerated conditions was meant to give pathogenic microbes enough time to die off.

Today, the forced pasteurization of young cheeses makes little sense. Pasteurization, like chemo, kills good and bad microbes alike. If pathogens get into the milk post-pasteurization, there is little to keep them from flourishing. "If you get on the CDC site, and you look up cheeses and past outbreaks, there are two that are raw milk and 11 to 13 that are pasteurized milk. So I understand the fear about the raw milk, but the pasteurized can be more dangerous," says Lekkas. Plus, studies of several cheese styles have documented the ability of a host of bacterial pathogens—including *Listeria*, *Salmonella*, *E. coli* and *Staphylococcus aureus*—to survive beyond the 60-day aging period. Yet outbreaks of human illness linked to raw milk cheese consumption are rarely reported. This remains true despite the tremendous growth in sales and consumption of artisan and traditional cheeses worldwide, which has exponentially increased consumer exposure to raw milk cheeses (Donnelly n.d.). (Raw milk cheeses are almost exclusively made by artisan producers, since they require more effort and are less easily standardized.)

Jasper Hill's specialization in raw milk cheese production is thus an implicit rebuke to an outdated regulatory regime. It would be much simpler to simply follow the FDA and USDA recommendation and use pasteurized milk, killing off all the microflora and then selectively reintroducing microbes by using commercial cultures. "We'd definitely make more money that way," says Mateo. But pasteurization destroys a vital link to the landscape, because it kills off all of the microorganisms in the milk that are the accumulation of dairy farming practices — milking, feeding, sheltering, etc. The result is milk that is a "blank slate" for the cheesemaker, anonymous milk that could come from anywhere. "If you can just pasteurize everything and make Alpha Tomen in Wisconsin, that's probably what would happen eventually. And that would not be a great thing for Greensboro."

The microbiology of cheese made from (mostly unpasteurized) Vermont milk therefore becomes a fundamentally important component distinguishing Jasper Hill cheeses. It also puts a large bullseye on the creamery's back: one *Listeria* or *E coli* outbreak, and it could be forced to shut down. Washington State's Estrella Family Creamery, which shut down after the FDA impounded more than $100,000 worth of hard cheese, despite the FDA only finding *Listeria* in its soft cheese, presents a cautionary tale (Neuman 2010b). The stress of being one slip-up away from disaster weighs on Lekkas, who is responsible for product safety at Jasper Hill. "There are sometimes nights I don't sleep because I think: did I do everything right? Did I miss anything?

There are times we have pulled cheese out because we were in compliance but we didn't feel safe." Nevertheless, the regulatory risk is worth it to Lekkas and to the Kehlers in order to make cheese that reflects the Northeast Kingdom.

Plus, the pasteurized stuff just doesn't taste as good. In 2002, *The New Yorker*'s Burkhard Bilger described the difference during a tasting of pasteurized and unpasteurized varieties with cheese expert Max McCalman:

> McCalman reached over and cut wedges from two Reblochon-style cheeses, one of pasteurized milk, the other of raw… The pasteurized version wasn't bad, with its musty orange rind and rich ivory pate. But the raw-milk Reblochon seemed to bypass the taste buds and tap directly into the brain, its sweet, nutty, earthy notes rising and expanding from register to register, echoing in the upper palate as though in a sound chamber. I thought of something one of the founders of the Cheese of Choice Coalition had said when I asked her what difference raw milk could possibly make: One is a cheese; the other is an aria by Maria Callas. (153-154)

The raw-milk Reblochon had a superior flavor profile to the pasteurized version because pasteurization kills much of the natural milk flora that contribute to flavor.

Milk pasteurization is not the only issue at play. The FDA has sought to establish stringent *E. coli* criteria that many artisan cheeses, regardless of whether produced from raw or pasteurized milk, simply cannot meet (Fletcher 2014). They have also attempted to ban the use of wooden boards in cheese aging. As in lambic breweries, the biofilms that form on these wood surfaces add flavor and character to the cheese, and do so safely. And the FDA has tried to ban the use of ash in cheesemaking, calling it a "non-permitted colorant." In fact, ash is a traditional material used for its alkalinity, which neutralizes the surface acidity of the curd, encouraging rind formation and protecting against excess mold growth during the ripening phase. Several beloved goat's milk cheeses from the Loire Valley use ash, such as Selles-sur-Cher and Sainte-Maure-de-Touraine (Marcellino and Benson 2016).

The continued global War on Microbes, and the lack of regulatory support for artisan producers, has real consequences. In Europe, centuries-old cheese styles like Fourme d'Ambert and Cantal are at risk of being lost in part because new health ordinances make them unaffordable or illegal to produce. In an impassioned speech at the Paris Climate Conference, Prince Charles decried the "bacteriological correctness of European regulators" (Chazan 2015). Meanwhile, artisan and industrial Camembert producers in France have been fighting a bitter legal and public relations battle for more than twenty-five years, informally called the Camembert Wars, over what constitutes traditional Camembert. The small producers were granted one of the earliest AOP labels, requiring that "Camembert de Normandie" be made from the raw milk of local Normandy cows. Industrial cheesemakers like Lactalis and Isigny Sainte-Mère, which produce most of the world's Camembert (ten times as much as all the artisan Camembert producers combined), use pasteurized milk and consequently are forbidden to use the "de Normandie" name. But since the industrial producers maintain factories in Normandy, they've confusingly been allowed to slap "Made in Normandy" on the label. In February 2018 France's Institute of Origin and Quality (INAO) stunningly ruled that industrial producers can simply use the AOP label as long as at least thirty percent of the milk comes from cows grazing in the Normandy region, whether the milk was pasteurized or not (Schrieberg 2018). The number of raw milk Camembert artisans is expected to wither as industrial manufacturers churn out AOP pasteurized Camembert.

In the U.S., artisan cheesemakers have had some successes defending against regulatory overreach and factory imitations. When the FDA proposed banning wooden boards in cheese aging in 2014, for instance, they flooded social media and their congressional representatives with protests. The FDA ended up backing off, issuing a "Constituent Update" indicating that media reports about their intentions were inaccurate. *Fortune* magazine was one of several mainstream media outlets to publish an incensed article on the back-and-forth (McNeal 2014).

In late 2015, Representative Peter Welch (D-VT) and Senators Patrick Leahy (D-VT) and Bernie Sanders (I-VT) helped quash the FDA's proposal for new *E. coli* standards, questioning "whether a new FDA standard calling for a thousand-fold decrease in the presence of non-toxigenic E. coli in raw milk cheeses would actually benefit public health" ("Welch, Leahy, Sanders Challenge FDA on New FDA Cheese Standard" 2015). Jasper Hill Farm played a crucial role in organizing the artisan cheese industry's response, demonstrating through microbiological studies that the FDA's proposed standards had no evidentiary basis, and that the standards would imperil an artisan cheese renaissance that is creating precious opportunities for dairy farmers and cheesemakers in rural economies facing challenging times.

What is at stake is the right of small producers to partner with microbes in ways that go back centuries, sometimes millennia, and to defend their products from cheap and sterile industrial cheeses. Panos Lekkas, Jasper Hill's passionate head scientist, ended our interview with an aggrieved monologue about a recent trip to a grocery store:

> I picked up a yogurt, Dannon or something, and it said 'artisanal yogurt.' It was almond milk yogurt, and on the back it said 'cured by traditional ways.' I was thinking 'No. NO!' My son was with me, and he was like dad, not now. I was like, 'Do you see this!' You need to say to yourself, hey, artisanal means something.

Lekkas's mission in life is to help the cheese industry inaugurate the first American PDO cheese. To do so, he believes that he needs to demonstrate a complete knowledge of the microbiology underlying Jasper Hill's cheese production, so that he can convey the ecosystem that Jasper Hill has built. "You've got to marry your industry to the science," he says.

Conclusion: Disgust, and Delight

I love cheese, the gooier and stinkier the better. In my kitchen there is a framed portrait of Harbison, Jasper Hill's bloomy-rind, bark-wrapped soft cheese. It's not especially stinky, but it is plenty gooey.

Figure 17*: "Harbison Halves," an oil painting by Mike Geno hanging in my kitchen.*

For the uninitiated, a very stinky cheese can invoke disgust. But that disgust is culturally learned. Fuschia Dunlop, an English food writer, captures the cultural element of disgust in her essay "Stinky Delicacies" (2016), published in *Cured*, a magazine dedicated to preserved foods. In it Dunlop describes forgetting she's left a bag of Tunworth, a British take on Camembert, in her gym bag. An odor wafts around her, and she wonders if her dinner companion has farted. As the smell follows her on her bus ride home, she grows paranoid that she might be losing control of her bodily functions. Then she remembers she visited a cheese shop earlier that morning, and the smell immediately becomes appetizing: “One moment I had been revolted and appalled; the next, I was thinking eagerly ahead to a midnight snack” (74).

Scientists have traditionally assumed that the powerful emotion of disgust evolved biologically, to protect early man from pathogens like those that might be found in rotting meat. A biological basis for disgust fits neatly into our understanding of evolution, but Paul Rozin (1999), a cultural psychologist at the University of Pennsylvania, points out that there are problems with it. For example, infants and very young children do not show a contamination response. Rozin tested this by putting a cockroach in a drink, removing it, and then seeing who would drink it. The children under 4-5 did, while the adults did not. Infants and very young children will also touch or even consume feces, as many parents will attest.

Rozin’s hypothesis is that disgust might not come from an avoidance of pathogens – which a contamination response would imply – but from a pre-adaptive toxin avoidance system. Rozin and his colleagues recognized that “there is a major difference between a biologically evolved poison rejection system and a microbe avoidance system” (“On the Origin of Disgust”). The physical basis of disgust (avoid poison) might then have evolved into a cultural basis for disgust. What disgusts you gastronomically, sexually, even interpersonally is helpful in identifying you within a clan. As Rozin writes in the same essay, “evolutionary psychologists don’t like to consider cultural evolution, although (1) cultural evolution, for the most part, works under the same principles as biological evolution, and (2) we can actually accumulate definitive evidence for cultural evolutionary origins, because they are more recent, and often leave records….”

The upshot is that disgust may be culturally learned, not biologically ingrained. Fermented foods illustrate this, in that every culture has their own traditions. As Sandor Katz writes in *The Art of Fermentation* (2012), “I have searched – without success – for examples of cultures that do not incorporate any form of fermentation” (6). But what is appetizing to you may be appalling to your foreign guest

With experience and familiarity, we overcome our culturally-learned distaste for certain foods. Perhaps, by a small leap of logic, learning more about the role that microbes play in our favorite foods can help us overcome culturally-ingrained antimicrobial attitudes. The switch flipped once before. The pioneers of microbiology were not disgusted by the animalcules they saw, they were fascinated. Leeuwenhoek, after finding a menagerie of life in his own dental plaque, went off and found an old man who was proud to say that he had never brushed his teeth in his life. “What a zoo of wee animals must be in this old fellow’s mouth,” he thought! (de Kruif 16).

The discovery of microbial life paradigmatically changed scientific thinking about the world and humanity’s place within it. It was not a negative or fearful change at first, but humbling and awe-inspiring. As the MIT anthropologist Ben Wurgaft explained:

> The use of the microscope to examine very small organisms in drops of water, or to examine a strand of one’s own hair and see what the structure of it was, was really world-changing, because it meant understanding that the scale of everyday human experience was not necessary the authoritative scale. Hundreds of years before Foucault, we have the displacement of the Anthropos as the center of the universe. Because in a very obvious way, the scale of things that make sense for humans to use as signposts to navigate their world, are suddenly not the only relevant thing anymore. Our sense of scale isn’t an Aristotelian mean for the universe.

It was only when Pasteur and his followers successfully fingered microbes as the causes of terrifying diseases that microbes became something to fear, ward off, eliminate. Percival and Percival (2017) point out that the term “germs” originally made sense for microbes, since it “reflects their status as organisms capable of growing and developing, like the seeds of a plant” (20). But the difference between a “germ” and a “pathogen” collapsed in the twentieth century.

Today the pendulum is swinging back, from disgust and fear to fascination and delight. As the microbiologist Nathan Wolfe (2014) put it in his Ted Talk:

> People think about the data revolution. Everyone is very interested in how much data is out there, and how much data does Facebook have and it seems like a tremendous amount. Well, I'll tell you right now that most of the information content of our planet is locked up in microbes, and the DNA and RNA of microorganisms. And we're only just starting to uncover what that means.

There is a Manifest Destiny-like rush among scientists and corporate interest to sequence as much of our unexplored microbial world as possible, as quickly as possible, and to look for solutions to human problems out of it. Microbiome research represents some of the most exciting and well-funded science happening today.

Fermented food producers, and their laboratory collaborators, put a public face on this frenzied microbial exploration. It seems fitting that artisans are helping end the Antimicrobial Age; after all, fermentation is man's most ancient partnership with microbes, entered into well before man maligned the microbe. Whether it is a brewery marketing wild yeast-fermented ales, a biotech coffeemaker marketing acidity-eating microbes, or a cheesemaker marketing the microbial ecology of the Northeast Kingdom, consumers learn more about microbes through their guts. And when consumers learn more about microbes they become enchanted by the biodiversity and ubiquity of microbial life, and call a truce in the War on Microbes.

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