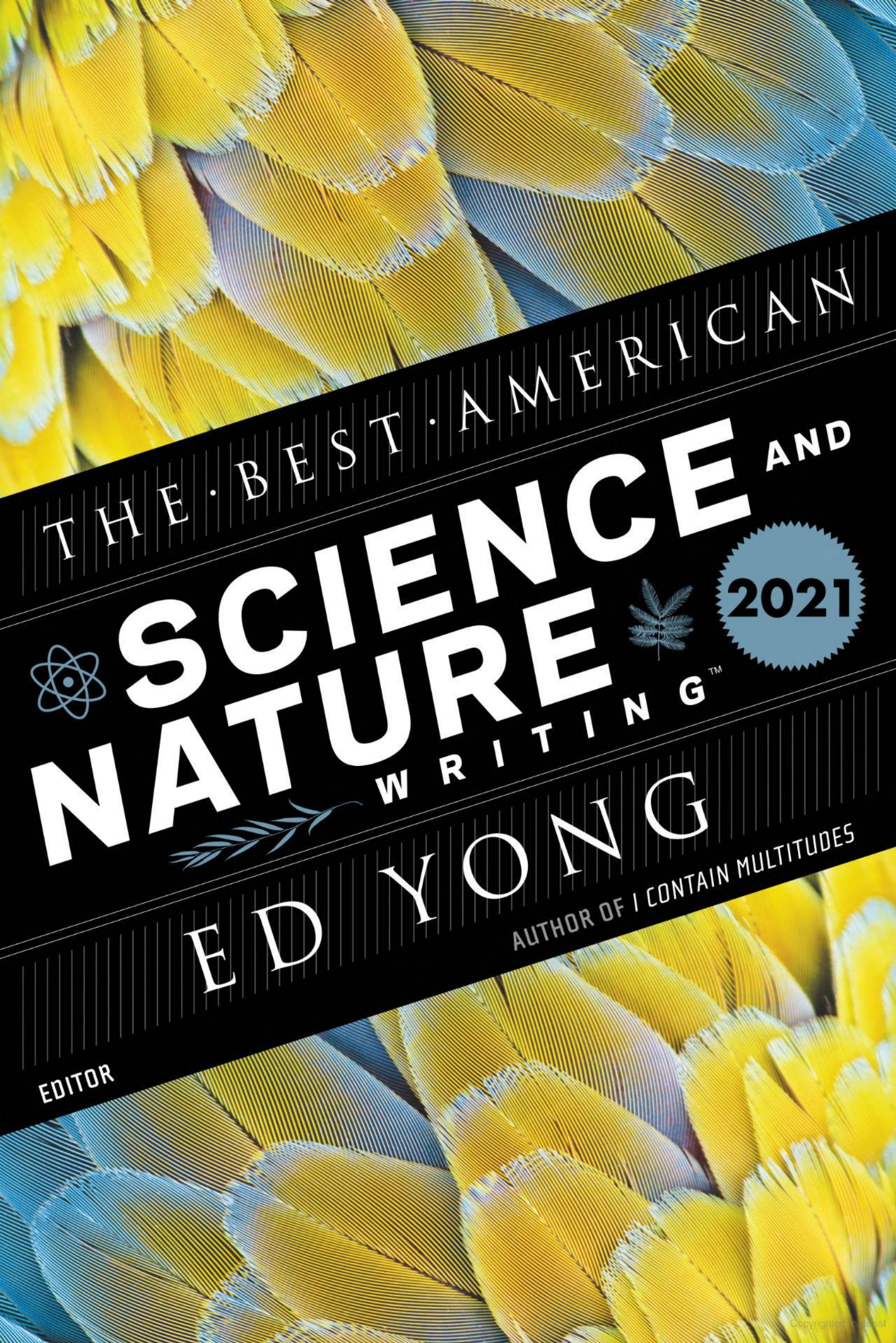

THE · BEST · AMERICAN SCIENCE AND NATURE WRITING™

2021

ED YONG

AUTHOR OF I CONTAIN MULTITUDES

EDITOR

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Foreword

One of the things I love about helping to edit this series is the breadth of stories I read and the breadth of stories we publish. But this year, of course, feels different. Alongside the essays about the cosmos and earthworms and our relationships with the outdoors are the essays about aerosol spread and exhausted physicians and insufficient recovery, trouble breathing and inequality and illness and death.

I can imagine futures where an unusual confluence of subject in this anthology reflects some thrilling advance or discovery—science and nature writing from the year we discover intelligent life beyond Earth?—and past years have had their own ripples, clusters of essays about animal extinctions, a yearly series of harrowing reporting on wildfires. But for 2020 this book is a portrait of a world upended, drawn in the work of writers who tried to make sense of it for us all.

This was a year when we desperately needed science writing, and also saw how science writing alone wasn't enough. As Ed Yong writes in his introduction, the Covid-19 pandemic was a crisis of science and nature and of so much more—politics, social tensions, education, inequality. It was an "omnicrisis," as Ed puts it, both because it touched on everything and because it was all-consuming. Any time I've been aware that I'm living through history has almost always been awful; 2020 was a whole year of that. But I'm writing this with one dose of a vaccine in my body, and having last week hugged my mom for the first time in over a year. Those moments were historic too. Last year in my foreword I looked out onto the rest of 2020 with thoughts of worlds ending; today there is, if I'm brave enough, some hope (and God I hope I haven't jinxed it).

While Ed spent 2020 as a reporter, I spent it as a reader, at least when it came to the coronavirus. Many science writers, like Ed and like my local paper's sports reporter, were wrangled into writing about the pandemic ("just for a few weeks," I think many of them were assured), but my work was elsewhere. So while I wrote about extraterrestrial life and edited essays about science and technology, my experience with regards to Covid was as a reader. And this year I found science and nature writing to be more vital than ever.

The pandemic revealed to us, over and over, the messy, fitful work of science. Hopefully anyone who once satisfiedly intoned, "I believe science," now sees that science is not a monolith but a process. And this year we watched that process with unprecedented scrutiny—not "we" the science writers, but "we" the public, "we" the people desperate for news and information and, most of all, guidance. We were told to wash our hands, and then told that surface transmission was minimal. We were told that masks were unnecessary, and then that they were our most essential defense, and then that to wear them outside was more deference to politics than public health. None of these changes and reconsiderations meant that science had failed us. Science, to the extent that it's a cohesive entity, was simply doing its job—gathering evidence, testing theories, refining our understanding of the world.

Through this morass, we turned to science writers to help us make sense of the sausage we were watching being made. I want to take a moment for one writer whose reporting you won't read in this anthology: Ed Yong. I've joked to friends that we asked Ed to edit this year's anthology because otherwise the book would have to be half his writing. In truth—well, in addition to that reasoning—I wanted Ed to edit this edition because I've trusted his writing and insight more than anyone else's this year. Prior to the pandemic, Ed did write a brilliant article titled "When the Next Plague Hits" (anthologized in the 2019 edition of this series), but he also wrote about the microbiome and hippo poop and duck penises. I always thought of him as one of the best and funniest science writers out there. This year he turned out to be one of the most vital as well.

Ed's writing on the pandemic offered synthesis and sensemaking of a senseless year. He illuminated and assuaged our fears while explaining the frightening realities of the moment. As hard as his writing was sometimes to read—especially for those of us who may have made it through the first months of the pandemic by dissociating just a tiny bit—I know that it was even harder to write. To not only make sense of the chaos but be immersed in it. This goes for all of the writers of the pandemic, in this anthology and elsewhere. So much gratitude.

In this year of survival, writers not only brought us news but made beauty and meaning. Some, like Ed, made sense of the omnicrisis, illuminating the invisible parallels and connections that united seemingly disparate forces and events and revealed the larger scales of significance. In "The Scramble to Pluck 24 Billion Cherries in Eight Weeks," Brooke Jarvis wrote about a seemingly simple, often invisible task—harvesting cherries—to uncover the economic, social, and scientific tensions woven into labor during a pandemic. Meehan Crist, in "What the Coronavirus Means for Climate Change," showed that compounding crises are never separate; instead, they all highlight the need for action and the hopeful possibility of another world. Julia Craven's "It's Not Too Late to Save Black Lives" emphasized the fact that for all that a virus cannot see race, inequality is so entrenched in our society that illness becomes a vector of racism too.

Other writers dove deep into the minutiae. In "They Say Coronavirus Isn't Airborne—but It's Definitely Borne by Air," Roxanne Khamsi addressed the scientific infighting that threatened the communication of some of the most important precautions against Covid. Heather Hogan delved deep into her personal experience with long Covid in "The Soft Butch That Couldn't (Or: I Got Covid-19 in March and Never Got Better)," writing with clarity and searing honesty.

As much as the pandemic was an omnicrisis, it was not all there was to write about this year. Less than half of this book is about it. There is also Shannon Stirone's sweeping story of attempts to map the cosmos and the human desire to understand our place in it; Katy Kelleher's beautiful meditation on the many meanings of a shade of violet; and Sarah Zhang's astonishing reporting, with depth and empathy, on how prenatal testing is changing what it means to be born with Down syndrome.

That's just a glimpse, but you already have the book in your hands. (You can find information for submitting work for consideration for future editions of this anthology at jaimegreen.net/BASN.) I hope you enjoy the beauty of these writers' work, learn more about the world, and perhaps reconnect with a tumultuous and traumatizing year. This is just one snapshot—or twenty-six of them—of history.

I ended last year's foreword with the wish, "I hope you're doing okay." I want to end this year's with a moment for the people who aren't, those who've lost loved ones to Covid, those whose lives have been upended. To the extent that this book is mine to dedicate (it's not, but I can dedicate the foreword at least), I'd like it to honor the memory of Rana Zoe Mungin, who died early in the pandemic, and horribly early in her life. Zoe was a brilliant fiction writer and a beloved soul. She was young, she had asthma, and she was Black; the first two times she sought emergency care for Covid, her concerns were diminished and dismissed. Zoe died on April 27, 2020, and her death will always be an injustice and a great loss. With love to Zoe's family and friends, and all of you.

Jaime Green

Introduction

I ENTERED 2020 THINKING of myself as a science writer. I ended the year less sure.

While the first sparks of the Covid-19 pandemic ignited at the end of 2019, I was traipsing through a hillside in search of radio-tagged rattlesnakes, allowing myself to get electrocuted by an electric catfish, and cradling loggerhead turtle hatchlings in the palm of my hand. As 2020 began and the new coronavirus commenced its ruinous sweep of the world, I was marveling at migratory moths and getting punched in the pinky by a very small and yet surprisingly powerful mantis shrimp. We share a reality with these creatures, but we experience it in profoundly different ways. The rattlesnake can sense—perhaps see—the body heat of its mammalian prey. The catfish can detect the electric fields that other animals involuntarily produce. The moths and the turtles can both sense the magnetic field of the planet and use it to guide their long navigations. The mantis shrimp sees forms of light that we cannot, and it processes colors in a way that no one fully understands. Each species has its own unique coterie of senses. Each is privy to its own narrow slice of the total sights, smells, sounds, and other stimuli that pervade the planet.

My plan was to write a book about those sensory experiences—a travelogue that would take people through the mind of a bat, a bird, or a spider. Such a journey, "not to visit strange lands but to possess other eyes," as Marcel Proust once said, is "the only true voyage."

It quickly became the only voyage I could make. As the pandemic spread, the possibility of international travel disappeared. Commuting turned from daily reality to fading memory. Restaurants, bars, and public spaces closed. Social gatherings became smaller, infrequent, and subject to barriers of cloth and distance. My world contracted to the radius of a few blocks, but the sensory worlds of other animals stayed open, magical and Narnia-like, accessible through the act of writing.

When I had to pause my book leave to report full-time on the pandemic, those worlds closed too.

In theory, 2020 should have been a banner year for science and nature writers. A virus upended the world and gripped its attention. Arcana of epidemiology and immunology—super-spreading, herd immunity, cytokine storms, mRNA vaccines—became dinner-table fodder. Public health experts (and pseudo-experts) gained massive followings on social media. Tony Fauci became a household name. The biggest story of the year—perhaps of the decade—was a science story, and science writers seemed ideally placed to tell it.

When done properly, covering science trains a writer to bring clarity to complexity, to embrace nuance, to run toward uncertainty instead of seeking easy answers, to understand that everything new is built upon old foundations, and to probe the unknown while delimiting the bounds of their own ignorance. The best science writers learn that science is not a procession of facts and breakthroughs, but an erratic stumble toward gradually diminished uncertainty; that peer-reviewed publications are not gospel and even prestigious journals are polluted by nonsense; and that the scientific endeavor is plagued by all-too-human failings like hubris. All of these qualities should have been invaluable in the midst of a global calamity, where clear explanations were needed, misinformation was rife, and answers were in high demand but short supply.

But the pandemic was not just a science story. It was an omnicrisis that warped and upended every aspect of our lives. While the virus assaulted our cells, it also besieged our societies, seeping into every crack and exploiting every weakness it could find. It found many. To understand why the United States fared so badly against Covid-19, despite its enormous wealth and biomedical savvy, one had to understand not just matters of virology but also the nation's history of racism and genocide, its carceral state, its nursing homes, its historical attitudes toward medicine and health, its national idiosyncrasies, the algorithms that govern social media, and the grossly deficient character of its forty-fifth president. I barely covered any of these issues in an eight-thousand-word piece about whether the United States was ready for the next pandemic that I wrote for the *Atlantic* in 2018 (reprinted in the 2019 edition of this anthology). When this pandemic started, my background as a science writer, and one who had specifically reported on pandemics, was undoubtedly useful, but to a limited degree—it gave me a half-mile head start, with a full marathon left to run. Throughout the year, many of my peers caviled about journalists from other beats who wrote about the pandemic without a foundation of expertise. But does anyone truly have the expertise to cover an omnicrisis that, by extension, is also an omnistory?

The all-encompassing nature of epidemics was clear to the German physician Rudolf Virchow, who investigated a typhus outbreak in 1848. Virchow knew nothing about the pathogen responsible for typhus, but he correctly realized that the outbreak was only possible because of poverty, malnutrition, poor sanitation, dangerous working conditions, and inequities perpetuated by incompetent politicians and negligent aristocrats. "Medicine is a social science and politics is nothing but medicine in larger scale," Virchow wrote.

This viewpoint was championed by many of his contemporaries, but it waned as germ theory waxed. In a bid to be objective and politically neutral, scientists focused their attention on pathogens that cause disease and ignored the societal factors that make disease possible. The social and biomedical sciences were cleaved apart, separated into different disciplines, departments, and scholars. Medicine and public health treated diseases as battles between individuals and germs, while sociologists and anthropologists dealt with the wider context that Virchow had identified. This rift began to narrow in the 1980s, but it still remains wide. Covid-19 landed in the middle of it. Throughout much of 2020, the United States (and the White House, specifically) looked to drugs and vaccines for salvation, while furiously debating about masks and social distancing. The latter were the only measures that controlled the pandemic for much of the year; billed as "non-pharmaceutical interventions," they were characterized in opposition to the more highly prized biomedical panaceas. Meanwhile, social interventions like paid sick leave and universal health care, which could have helped so-called essential workers protect their livelihoods without risking their health, were barely considered.

To the extent that the pandemic was a science story, it was also a story about the limitations of what science has become. Perverse academic incentives that reward researchers primarily for publishing papers in high-impact journals have long pushed entire fields toward sloppy, irreproducible work; during the pandemic, scientists flooded the literature with similarly half-baked and misleading research. Pundits urged people to "listen to the science," as if "the science" is a tome of facts and not an amorphous, dynamic entity, born from the collective minds of thousands of individual people who argue and disagree about data that can be interpreted in a range of ways. The long-standing disregard for chronic illnesses like dysautonomia and myalgic encephalomyelitis meant that when thousands of Covid-19 "long-haulers" kept on experiencing symptoms for months, science had almost nothing to offer them. The naive desire for science to remain above politics meant that many researchers were unprepared to cope with a global crisis that was both scientific and political to its core. "There's an ongoing conversation about whether we should do advocacy work or 'stick to the science,'" Whitney Robinson Rivers, a social epidemiologist, told me. "We always talk about how these magic people will take our findings and implement them. We send those findings out and knowledge has increased! But with Covid, that's a lie!"

Virchow's experiences with epidemics radicalized him, pushing the man who would later become known as the "father of pathology" to advocate for social and political reforms. Covid-19 has done the same for many scientists. Many of the issues it brought up were miserably familiar to climate scientists, who drolly welcomed newly traumatized epidemiologists into their ranks. In the light of the pandemic, old debates about whether science (and science writing) is political—many of which have been captured in the introductions of this anthology series—now seem small and antiquated. Science *is undoubtedly political* whether scientists want it to be or not, because it is an inextricably human enterprise. It belongs to society. It is interleaved with society. It is of society.

This is true even of areas of science that seem to be sheltered within some protected corner of intellectual space. My first book was about the microbiome, a bustling area of research that went unnoticed for centuries because it had the misfortune to arise amid the ascent of Darwinism and germ theory. With nature red in tooth and claw, and germs as the root of disease, the idea of animals benefiting from cooperative microbes was anathema. My next book will show that our understanding of animal senses has been influenced by the sociology of science—whether scientists believe one another, whether they successfully communicate their ideas, whether they publish in a prestigious English journal or an obscure foreign-language one. That understanding has also been repeatedly swayed by the trappings of our own senses. Science is often caricatured as a purely empirical and objective pursuit. But in reality, a scientist's interpretation of the world is influenced by the data she collects, which are influenced by the experiments she designs, which are influenced by the questions she thinks to asks, which are influenced by her identity, her values, her predecessors, and her imagination.

When I began to cover Covid-19 in 2020, it became clear that the usual mode of science writing would be grossly insufficient. Much of journalism is fragmentary: big stories are broken down into small components that can be quickly turned into content. For science writing, that means treating individual papers as a sacrosanct atomic unit and writing about them one at a time. But for an omnicrisis, this approach only leads to a messy, confusing, and ever-shifting mound of jigsaw pieces. What I tried to do instead was to unite those pieces. I wrote a series of long features about big issues, attempting to synthesize vast amounts of information and give readers a steady rock upon which they could observe the torrent of information rushing past them without drowning in it. I treated the pandemic as more than a science story, interviewing sociologists, anthropologists, historians, linguists, patients, and more. And I found that the writing I gravitated toward myself did the same. The pandemic clarified that science is inseparable from the rest of society, and that connection works both ways. Science touches on everything; everything touches on science. The walls between beats seemed to crumble. What, I found myself asking, even counts as science writing?

Which is an interesting question to be asking yourself just as you're asked to edit an anthology of science and nature writing.

This is not an anthology about Covid-19, although the pandemic is central to eleven of the twenty-six pieces. This is very much an anthology, however, that reflects a tumultuous, pandemic-suffused year. The stories I have chosen reflect where I feel the field of science and nature writing has landed, and where it could go. They are often full of tragedy, sometimes laced with wonder, but always deeply aware that science does not exist in a social vacuum. They are beautiful, whether in their clarity of ideas, the elegance of their prose, or often both. They extend laterally, into areas that might not traditionally fall within the bucket of science writing. They stretch temporally, drawing on history for context and sending imaginative tendrils into the future. They synthesize, evaluate, dig, unveil, and challenge.

I've loosely organized the pieces into three sections. The first, "Contagion," is entirely about Covid-19. These pieces are not just about the pandemic, but about what the pandemic has revealed about the world in which we live. Zeynep Tufekci leads the set by explaining the crucial idea of overdispersion—the burstiness of the virus's spread. This concept not only explains why some areas were pummeled by the coronavirus while others escaped unscathed, but also why it has been so hard to absorb lessons from the pandemic. Overdispersion, Tufekci writes, "interferes with how we ordinarily think about cause and effect" and our desire to draw patterns from randomness and sense from tragedy.

Next up, Roxanne Khamsi questions the official pronouncements that the coronavirus was not airborne, in a remarkably prescient piece that preceded debates about aerosol transmission by many months. A seemingly simple matter—airborne or not?—boils down to long-standing academic debates about how that word is even defined, Khamsi shows. Amanda Mull then explores why so many Americans seemed bent on taking undue risks in a generation-defining crisis. Drawing on sociology and psychology, she punctures the all-too-common idea that people will simply change their minds if provided with the right information, and she shows how tribal identities, mixed messages, and irresponsible institutions trapped the United States in a cycle of bad decisions.

Drawing on her own experiences and those of Italian colleagues, Helen Ouyang vividly describes the horrors of working in a hospital that was being overwhelmed by a new disease. Susan Dominus reports on the civil wars that arose between frontline clinicians, who were torn between the need to try something, anything, right now, and the need to accumulate evidence about what treatments actually worked. Heather Hogan writes beautifully about her own experiences as one of the first people in the United States to deal with the symptoms of "long Covid," at a time when the phenomenon was still unknown—"I was the science," she says. In these pieces, the pandemic reveals the edges and weaknesses of modern medicine. In the next, it exposes the flaws in broader society.

Covid-19 laid bare the grievous neglect that we have allowed to befall our elderly, as Katie Engelhart details in her story about the Life Care Center of Kirkland, Washington—a nursing home that was the first Covid-19 hotspot in the United States. The pandemic showed the discriminatory care that Black people have long received, as Julia Craven reveals by juxtaposing the stories of two women against a sweeping look at America's centuries-old legacy of racism. It also showed that people who are billed as "essential" are often treated as disposable, as Brooke Jarvis demonstrates in her piece about the largely immigrant workforce compelled to pick 24 billion cherries in eight weeks. Taking in agricultural science, immigration politics, and the pandemic itself, Jarvis exposes what has been invisible to us: the people behind the fragile system that brings food to our fridges. These stories show that the products of science and technology—longer lives, better health, and readier food—do not exist in a social vacuum but are instead distributed according to whom society values, and whom it does not.

The second section, "Connections," takes a deeper dive into the intimate links between science and humanity at large. Susan Orlean writes about a different pandemic—rabbit hemorrhagic disease. Its recent invasion of the United States can best be understood in the context of humanity's relationship with rabbits, animals that we uniquely treat as both pets and food. Shannon Stirone contrasts a grand plan to create the most detailed 3-D map of the universe against our ancient desire to understand ourselves in the context of where we are and what lies beyond. As part of a series on colors, Katy Kelleher illuminates our cultural connection with periwinkles and purples in a whirlwind essay that takes in botany, oncology, color theory, and art history.

Though science often concerns itself with literally universal mysteries, it is also an acutely personal endeavor, molded by the identities and stories of scientists themselves. Sabrina Imbler tells the story of Elke Mackenzie, a transgender scientist who was one of lichenology's unsung heroes, but whose work and legacy is largely credited to her deadname. In their piece, Imbler portrays a woman who studied organisms that are famously hard to classify and who, "against ease and tradition, did not wish to separate her identity from her research." Jennifer Senior ponders on the life and suicide of psychologist Philip Brickman, who studied the nature of happiness while simultaneously struggling to find it amid the unrelenting pressures of academia.

Latria Graham writes a poignant letter about the challenges of being Black in the outdoors and exploring wild spaces in which she is not always welcome. Bathsheba Demuth, who got Covid-19 in the midst of yet another year of alarming climate change, ruminates on our ability to acclimatize to tragedy: "On the first day of summer, Siberia and I were the same temperature," she writes. Finally, Emily Raboteau catalogs a year of conversations about climate; part diary and part poetry collection, her wonderfully creative piece shows just how immediate and far-reaching climate change truly is.

Climate change looms large over the third and final section, "Consequences," which examines the costs of past and present sins. In a sweeping piece of evidence-based imagination, Meehan Crist considers the effect that the coronavirus might have on our climate; in the overlap between two planetary problems, Crist sees both the unsustainability of modern life and "a rare opportunity, even in the midst of great suffering, for rewiring our sense of what is possible in American society." Climate change is also exacerbating the downfall of the Kariba Dam at the border between Zambia and Zimbabwe—an imminent catastrophe that Namwali Serpell connects to the arrogance and evils of colonialism. Back in the United States, the combination of colonialism and human-caused climate change is also threatening the endangered Yaqui catfish. In the fish's looming extinction, Maya L. Kapoor finds a deeper message about our tendency to destroy nature while asking everything from it.

From global warming to global worming: Julia Rosen explains that earthworms are not native to the eastern United States but were introduced by people who held the Eurocentric idea that worms are good. They aren't good universally, and in their new ranges these ecosystem engineers have reengineered ecosystems to their detriment. Native animals, meanwhile, are disappearing. The monarch butterfly, once "the most ordinary of extraordinary things," in the words of Nora Caplan-Bricker, is now in decline. But by following the people who are toiling to preserve this iconic insect, Caplan-Bricker finds desperation and hope, "the joy of living on this damaged planet, and a will to witness whatever comes next." Rosanna Xia discovers a similar blend of emotions among the scientists who uncovered up to half a million barrels of DDT that were dumped off Santa Catalina Island and are now leaking into the ocean. DDT was once billed as one of science's greatest achievements, but it is now, as Xia shows, a toxic legacy for which we don't have a plan.

The march of science and technology is still leaving a trail of unintended and treacherous potholes. In Boca Chica, Texas, Marina Koren meets the people who became unwitting neighbors to the rocket company SpaceX, their tranquil paradise punctured by Elon Musk's Martian ambitions. In Yangquan, China, Jiayang Fan profiles the Friendship and Love Hospital—a rare hospice in a country where prosperity and taboos around death have left an aging population with little in the way of end-of-life care. And finally, in what is perhaps my favorite piece in this high-caliber collection, Sarah Zhang travels to Denmark, where nigh-universal screening for Down syndrome has dramatically reduced the number of children born with the condition. "The forces of scientific progress are now marching toward ever more testing to detect ever more genetic conditions," Zhang writes, and the route of that march will be defined by our attitude to disability and parenthood. "Recent advances in genetics provoke anxieties about a future where parents choose what kind of child to have, or not have. But that hypothetical future is already here. It's been here for an entire generation."

Some of the writers in this anthology would bill themselves as science or nature writers, but many would not. I consider this a strength. There has long been a view of science writing that imagines it's about opening up the ivory tower and making its obscure contents accessible to the masses. But this is a strange model, laden with troubling corollaries. It implicitly assumes that science is beleaguered and unappreciated, and that unwilling audiences must be convinced of its importance and value. It equates science with journals, universities, and other grand institutions that are indeed opaque and cloistered. And treating science as a special entity that normies are finally being invited to take part in is also somewhat patronizing.

Such invitations are not anyone's to extend. Science is so much more than a library of publications, or the opinions of doctorate-holders and professors. Science writing should be equally expansive. Earlier, I asked: *What even counts as science writing?* Now, here's my reply: *We shouldn't be able to answer that question.* A woman's account of her own illness. A cultural history of a color. An investigation into sunken toxic barrels. A portrait of a town with a rocket company for a neighbor. To me, these pieces show that science and nature are intricately woven into the fabric of our lives—so intricately that science and nature writing *should* be difficult to categorize.

There is an obvious risk here. Of the typical journalistic beats, science is perhaps the only one that draws us out of our human trappings. Culture, politics, business, sport, food: these are all about one species. Science covers the other billions, and the entirety of the universe besides. I feel its expansive nature keenly. I have devoted most of my career to writing about microbes and lichens, hagfish and giraffes, duck penises and hippo poop. I am writing this introduction having resumed my book leave, to finish my travelogue of animal senses. But I do so with a renewed understanding that even as we step away from ourselves, we cannot fully escape. Our understanding of nature has been profoundly shaped by our culture, our social norms, and our collective decisions about who gets to be a scientist at all. And our relationship with nature—whether we succumb to it, whether we learn from it, whether we can save it—depends on our collective decisions too.

I hope this anthology acts as a guide for making better decisions. It is an unusually melancholy medley, and while I didn't deliberately craft it that way, it feels like a fitting reflection of the state of the world at the start of 2021. The pandemic showed us how much we need to fix, and fortunately, science is famous for its capacity to self-correct. The pandemic also revealed the need for unity and connection, to save one another and to feel alive. Good science writing—the best science writing—illuminates those connections, between us and the rest of the world. Even when it is melancholy, I find it beautiful. And I believe it can lead us toward the kind of radical introspection that we so sorely need.

Ed Yong

Contagion

ZEYNEP TUFEKCI

This Overlooked Variable Is the Key to the Pandemic

FROM *The Atlantic*

THERE'S SOMETHING STRANGE about this coronavirus pandemic. Even after months of extensive research by the global scientific community, many questions remain open.

Why, for instance, was there such an enormous death toll in northern Italy, but not the rest of the country? Just three contiguous regions in northern Italy have 25,000 of the country's nearly 36,000 total deaths; just one region, Lombardy, has about 17,000 deaths. Almost all of these were concentrated in the first few months of the outbreak. What happened in Guayaquil, Ecuador, in April, when so many died so quickly that bodies were abandoned in the sidewalks and streets? Why, in the spring of 2020, did so few cities account for a substantial portion of global deaths, while many others with similar density, weather, age distribution, and travel patterns were spared? What can we really learn from Sweden, hailed as a great success by some because of its low case counts and deaths as the rest of Europe experiences a second wave, and as a big failure by others because it did not lock down and suffered excessive death rates earlier in the pandemic? Why did widespread predictions of catastrophe in Japan not bear out? The baffling examples go on.

I've heard many explanations for these widely differing trajectories over the past nine months—weather, elderly populations, vitamin D, prior immunity, herd immunity—but none of them explains the timing or the scale of these drastic variations. But there *is* a potential, overlooked way of understanding this pandemic that would help answer these questions, reshuffle many of the current heated arguments, and, crucially, help us get the spread of Covid-19 under control.

By now many people have heard about R0—the basic reproductive number of a pathogen, a measure of its contagiousness on average. But unless you've been reading scientific journals, you're less likely to have encountered *k,* the measure of its dispersion. The definition of *k* is a mouthful, but it's simply a way of asking whether a virus spreads in a steady manner or in big bursts, whereby one person infects many, all at once. After nine months of collecting epidemiological data, we know that this is an *overdispersed* pathogen, meaning that it tends to spread in clusters, but this knowledge has not yet fully entered our way of thinking about the pandemic—or our preventive practices.

The now-famed R0 (pronounced as "r-naught") is an *average* measure of a pathogen's contagiousness, or the mean number of susceptible people expected to become infected after being exposed to a person with the disease. If one ill person infects three others on average, the R0 is three. This parameter has been widely touted as a key factor in understanding how the pandemic operates. News media have produced multiple explainers and visualizations for it. Movies praised for their scientific accuracy on pandemics are lauded for having characters explain the "all-important" R0. Dashboards track its real-time evolution, often referred to as R or Rt, in response to our interventions. (If people are masking and isolating or immunity is rising, a disease can't spread the same way anymore, hence the difference between R0 and R.)

Unfortunately, averages aren't always useful for understanding the distribution of a phenomenon, especially if it has widely varying behavior. If Amazon's CEO, Jeff Bezos, walks into a bar with 100 regular people in it, the average wealth in that bar suddenly exceeds $1 billion. If I also walk into that bar, not much will change. Clearly, the average is not that useful a number to understand the distribution of wealth in that bar, or how to change it. Sometimes, the mean is not the message. Meanwhile, if the bar has a person infected with Covid-19, and if it is also poorly ventilated and loud, causing people to speak loudly at close range, almost everyone in the room could potentially be infected—a pattern that's been observed many times since the pandemic begin, and that is similarly not captured by R. That's where the dispersion comes in.

There are Covid-19 incidents in which a single person likely infected 80 percent or more of the people in the room in just a few hours. But, at other times, Covid-19 can be surprisingly much less contagious. Overdispersion and super-spreading of this virus are found in research across the globe. A growing number of studies estimate that a majority of infected people may not infect a single other person. A recent paper found that in Hong Kong, which had extensive testing and contact tracing, about 19 percent of cases were responsible for 80 percent of transmission, while 69 percent of cases did not infect another person. This finding is not rare: multiple studies from the beginning have suggested that as few as 10 to 20 percent of infected people may be responsible for as much as 80 to 90 percent of transmission, and that many people barely transmit it.

This highly skewed, imbalanced distribution means that an early run of bad luck with a few super-spreading events, or clusters, can produce dramatically different outcomes even for otherwise similar countries. Scientists looked globally at known early-introduction events, in which an infected person comes into a country, and found that in some places, such imported cases led to no deaths or known infections, while in others, they sparked sizable outbreaks. Using genomic analysis, researchers in New Zealand looked at more than half the confirmed cases in the country and found a staggering 277 *separate* introductions in the early months, but also that only 19 percent of introductions led to more than one additional case. A recent review shows that this may even be true in congregate living spaces, such as nursing homes, and that multiple introductions may be necessary before an outbreak takes off. Meanwhile, in Daegu, South Korea, just one woman, dubbed Patient 31, generated more than 5,000 known cases in a megachurch cluster.

Unsurprisingly, SARS-CoV, the previous incarnation of SARS-CoV-2 that caused the 2003 SARS outbreak, was also overdispersed in this way: the majority of infected people did not transmit it, but a few super-spreading events caused most of the outbreaks. MERS, another coronavirus cousin of SARS, also appears overdispersed, but luckily, it does not—yet—transmit well among humans.

This kind of behavior, alternating between being super-infectious and fairly non-infectious, is exactly what *k* captures, and what focusing solely on R hides. Samuel Scarpino, an assistant professor of epidemiology and complex systems at Northeastern, told me that this has been a huge challenge, especially for health authorities in Western societies, where the pandemic playbook was geared toward the flu—and not without reason, because pandemic flu *is* a genuine threat. However, influenza does not have the same level of clustering behavior.

We can think of disease patterns as leaning deterministic or stochastic: in the former, an outbreak's distribution is more linear and predictable; in the latter, randomness plays a much larger role and predictions are hard, if not impossible, to make. In deterministic trajectories, we expect what happened yesterday to give us a good sense of what to expect tomorrow. Stochastic phenomena, however, don't operate like that—the same inputs don't always produce the same outputs, and things can tip over quickly from one state to the other. As Scarpino told me, "Diseases like the flu are pretty nearly deterministic and R0 (while flawed) paints about the right picture (nearly impossible to stop until there's a vaccine)." That's not necessarily the case with super-spreading diseases.

Nature and society are replete with such imbalanced phenomena, some of which are said to work according to the Pareto principle, named after the sociologist Vilfredo Pareto. Pareto's insight is sometimes called the 80 / 20 principle—80 percent of outcomes of interest are caused by 20 percent of inputs—though the numbers don't have to be that strict. Rather, the Pareto principle means that a small number of events or people are responsible for the majority of consequences. This will come as no surprise to anyone who has worked in the service sector, for example, where a small group of problem customers can create almost all the extra work. In cases like those, booting just those customers from the business or giving them a hefty discount may solve the problem, but if the complaints are evenly distributed, different strategies will be necessary. Similarly, focusing on the R alone, or using a flu-pandemic playbook, won't necessarily work well for an overdispersed pandemic.

Hitoshi Oshitani, a member of the National Covid-19 Cluster Taskforce at Japan's Ministry of Health, Labour, and Welfare and a professor at Tohoku University who told me that Japan focused on the overdispersion impact from early on, likens his country's approach to looking at a forest and trying to find the clusters, not the trees. Meanwhile, he believes, the Western world was getting distracted by the trees, and got lost among them. To fight a super-spreading disease effectively, policymakers need to figure out why super-spreading happens, and they need to understand how it affects everything, including our contact-tracing methods and our testing regimes.

There may be many different reasons a pathogen super-spreads. Yellow fever spreads mainly via the mosquito *Aedes aegypti,* but until the insect's role was discovered, its transmission pattern bedeviled many scientists. Tuberculosis was thought to be spread by close-range droplets until an ingenious set of experiments proved that it was airborne. Much is still unknown about the super-spreading of SARS-CoV-2. It might be that some people are super-emitters of the virus, in that they spread it a lot more than other people. Like other diseases, contact patterns surely play a part: a politician on the campaign trail or a student in a college dorm is very different in how many people they could potentially expose compared with, say, an elderly person living in a small household. However, looking at nine months of epidemiological data, we have important clues to some of the factors.

In study after study, we see that super-spreading clusters of Covid-19 almost overwhelmingly occur in poorly ventilated, indoor environments where many people congregate over time—weddings, churches, choirs, gyms, funerals, restaurants, and such—especially when there is loud talking or singing without masks. For super-spreading events to occur, multiple things have to be happening at the same time, and the risk is not equal in every setting and activity, Müge Çevik, a clinical lecturer in infectious diseases and medical virology at the University of St Andrews and a co-author of a recent extensive review of transmission conditions for Covid-19, told me.

Çevik identifies "prolonged contact, poor ventilation, [a] highly infectious person, [and] crowding" as the key elements for a super-spreader event. Super-spreading can also occur indoors beyond the six-feet guideline, because SARS-CoV-2, the pathogen causing Covid-19, can travel through the air and accumulate, especially if ventilation is poor. Given that some people infect others before they show symptoms, or when they have very mild or even no symptoms, it's not always possible to know if we are highly infectious ourselves. We don't even know if there are more factors yet to be discovered that influence super-spreading. But we don't need to know all the *sufficient* factors that go into a super-spreading event to avoid what seems to be a *necessary* condition most of the time: many people, especially in a poorly ventilated indoor setting, and especially not wearing masks. As Natalie Dean, a biostatistician at the University of Florida, told me, given the huge numbers associated with these clusters, targeting them would be very effective in getting our transmission numbers down.

Overdispersion should also inform our contact-tracing efforts. In fact, we may need to turn them upside down. Right now, many states and nations engage in what is called forward or prospective contact tracing. Once an infected person is identified, we try to find out with whom they interacted afterward so that we can warn, test, isolate, and quarantine these potential exposures. But that's not the only way to trace contacts. And, because of overdispersion, it's not necessarily where the most bang for the buck lies. Instead, in many cases, we should try to work *backwards* to see who first infected the subject.

Because of overdispersion, most people will have been infected by someone who also infected other people, because only a small percentage of people infect many at a time, whereas most infect zero or maybe one person. As Adam Kucharski, an epidemiologist and the author of the book *The Rules of Contagion,* explained to me, if we can use retrospective contact tracing to find the person who infected our patient, and *then* trace the forward contacts of the infecting person, we are generally going to find a lot more cases compared with forward-tracing contacts of the infected patient, which will merely identify *potential* exposures, many of which will not happen anyway, because most transmission chains die out on their own.

The reason for backward tracing's importance is similar to what the sociologist Scott L. Feld called the friendship paradox: your friends are, on average, going to have more friends than you. (Sorry!) It's straightforward once you take the network-level view. Friendships are not distributed equally; some people have a lot of friends, and your friend circle is more likely to include those social butterflies, because how could it not? They friended you and others. And those social butterflies will drive up the average number of friends that your friends have compared with you, a regular person. (Of course, this will not hold for the social butterflies themselves, but overdispersion means that there are much fewer of them.) Similarly, the infectious person who is transmitting the disease is like the pandemic social butterfly: the average number of people they infect will be much higher than most of the population, who will transmit the disease much less frequently. Indeed, as Kucharski and his co-authors show mathematically, overdispersion means that "forward tracing alone can, on average, identify at most the mean number of secondary infections (i.e. R)"; in contrast, "backward tracing increases this maximum number of traceable individuals by a factor of 2–3, as index cases are more likely to come from clusters than a case is to generate a cluster."

Even in an overdispersed pandemic, it's not pointless to do forward tracing to be able to warn and test people, *if* there are extra resources and testing capacity. But it doesn't make sense to do forward tracing while not devoting enough resources to backward tracing and finding clusters, which cause so much damage.

Another significant consequence of overdispersion is that it highlights the importance of certain kinds of rapid, cheap tests. Consider the current dominant model of test and trace. In many places, health authorities try to trace and find forward contacts of an infected person: everyone they were in touch with since getting infected. They then try to test all of them with expensive, slow, but highly accurate PCR (polymerase chain reaction) tests. But that's not necessarily the best way when clusters are so important in spreading the disease.

PCR tests identify RNA segments of the coronavirus in samples from nasal swabs—like looking for its signature. Such diagnostic tests are measured on two different dimensions: Are they good at identifying people who are not infected (specificity), and are they good at identifying people who are infected (sensitivity)? PCR tests are highly accurate for both dimensions. However, PCR tests are also slow and expensive, and they require a long, uncomfortable swab up the nose at a medical facility. The slow processing times means that people don't get timely information when they need it. Worse, PCR tests are so responsive that they can find tiny remnants of coronavirus signatures long after someone has stopped being contagious, which can cause unnecessary quarantines.

Meanwhile, researchers have shown that rapid tests that are very accurate for identifying people who do *not* have the disease, but not as good at identifying infected individuals, can help us contain this pandemic. As Dylan Morris, a doctoral candidate in ecology and evolutionary biology at Princeton, told me, cheap, low-sensitivity tests can help mitigate a pandemic even if it is not overdispersed, but they are particularly valuable for cluster identification during an overdispersed one. This is especially helpful because some of these tests can be administered via saliva and other less-invasive methods, and be distributed outside medical facilities.

In an overdispersed regime, identifying *transmission events* (someone infected someone else) is more important than identifying *infected individuals*. Consider an infected person and their twenty forward contacts—people they met since they got infected. Let's say we test ten of them with a cheap, rapid test and get our results back in an hour or two. This isn't a great way to determine exactly who is sick out of that ten, because our test will miss some positives, but that's fine for our purposes. If everyone is negative, we can act as if nobody is infected, because the test is pretty good at finding negatives. However, the moment we find a few transmissions, we know we may have a super-spreader event, and we can tell all twenty people to assume they are positive and to self-isolate—if there are one or two transmissions, there are likely more, exactly because of the clustering behavior. Depending on age and other factors, we can test those people individually using PCR tests, which can pinpoint who is infected, or ask them all to wait it out.

Scarpino told me that overdispersion also enhances the utility of other aggregate methods, such as wastewater testing, especially in congregate settings like dorms or nursing homes, allowing us to detect clusters without testing everyone. Wastewater testing also has low sensitivity; it may miss positives if too few people are infected, but that's fine for population-screening purposes. If the wastewater testing is signaling that there are *likely* no infections, we do not need to test everyone to find every last potential case. However, the moment we see signs of a cluster, we can rapidly isolate everyone, again while awaiting further individualized testing via PCR tests, depending on the situation.

Unfortunately, until recently, many such cheap tests had been held up by regulatory agencies in the United States, partly because they were concerned with their relative lack of accuracy in identifying positive cases compared with PCR tests—a worry that missed their population-level usefulness for this particular overdispersed pathogen.

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To return to the mysteries of this pandemic, what *did* happen early on to cause such drastically different trajectories in otherwise similar places? Why haven't our usual analytic tools—case studies, multi-country comparisons—given us better answers? It's not intellectually satisfying, but because of the overdispersion and its stochasticity, there may not be an explanation beyond that the worst-hit regions, at least initially, simply had a few unlucky early super-spreading events. It wasn't just pure luck: dense populations, older citizens, and congregate living, for example, made cities around the world more susceptible to outbreaks compared with rural, less dense places and those with younger populations, less mass transit, or healthier citizenry. But why Daegu in February and not Seoul, despite the two cities being in the same country, under the same government, people, weather, and more? As frustrating as it may be, sometimes, the answer is merely where Patient 31 and the megachurch she attended happened to be.

Overdispersion makes it harder for us to absorb lessons from the world, because it interferes with how we ordinarily think about cause and effect. For example, it means that events that result in spreading and nonspreading of the virus are asymmetric in their ability to inform us. Take the highly publicized case in Springfield, Missouri, in which two infected hairstylists, both of whom wore masks, continued to work with clients while symptomatic. It turns out that no apparent infections were found among the 139 exposed clients (67 were directly tested; the rest did not report getting sick). While there is a lot of evidence that masks are crucial in dampening transmission, that event *alone* wouldn't tell us if masks work. In contrast, studying transmission, the rarer event, can be quite informative. Had those two hairstylists transmitted the virus to large numbers of people despite everyone wearing masks, it would be important evidence that, perhaps, masks aren't useful in preventing super-spreading.

Comparisons, too, give us less information compared with phenomena for which input and output are more tightly coupled. When that's the case, we can check for the presence of a factor (say, sunshine or vitamin D) and see if it correlates with a consequence (infection rate). But that's much harder when the consequence can vary widely depending on a few strokes of luck, the way that the wrong person was in the wrong place sometime in mid-February in South Korea. That's one reason multi-country comparisons have struggled to identify dynamics that sufficiently explain the trajectories of different places.

Once we recognize super-spreading as a key lever, countries that look as if they were too relaxed in some aspects appear very different, and our usual polarized debates about the pandemic are scrambled too. Take Sweden, an alleged example of the great success or the terrible failure of herd immunity without lockdowns, depending on whom you ask. In reality, although Sweden joins many other countries in failing to protect elderly populations in congregate-living facilities, its measures that target super-spreading have been stricter than many other European countries. Although it did not have a complete lockdown, as Kucharski pointed out to me, Sweden imposed a fifty-person limit on indoor gatherings in March, and did not remove the cap even as many other European countries eased such restrictions after beating back the first wave. (Many are once again restricting gathering sizes after seeing a resurgence.) Plus, the country has a small household size and fewer multigenerational households compared with most of Europe, which further limits transmission and cluster possibilities. It kept schools fully open without distancing or masks, but only for children under sixteen, who are unlikely to be super-spreaders of this disease. Both transmission and illness risks go up with age, and Sweden went all online for higher-risk high school and university students—the opposite of what we did in the United States. It also encouraged social distancing, and closed down indoor places that failed to observe the rules. From an overdispersion and super-spreading point of view, Sweden would not necessarily be classified as among the most lax countries, but nor is it the most strict. It simply doesn't deserve this oversize place in our debates assessing different strategies.

Although overdispersion makes some usual methods of studying causal connections harder, we can study failures to understand which conditions turn bad luck into catastrophes. We can also study sustained success, because bad luck will eventually hit everyone, and the response matters.

The most informative case studies may well be those who had terrible luck initially, like South Korea, and yet managed to bring about significant suppression. In contrast, Europe was widely praised for its opening early on, but that was premature; many countries there are now experiencing widespread rises in cases and look similar to the United States in some measures. In fact, Europe's achieving a measure of success this summer and relaxing, including opening up indoor events with larger numbers, is instructive in another important aspect of managing an overdispersed pathogen: compared with a steadier regime, success in a stochastic scenario can be more fragile than it looks.

Once a country has too many outbreaks, it's almost as if the pandemic switches into "flu mode," as Scarpino put it, meaning high, sustained levels of community spread even though a majority of infected people may not be transmitting onward. Scarpino explained that barring truly drastic measures, once in that widespread and elevated mode, Covid-19 can keep spreading because of the sheer number of chains already out there. Plus, the overwhelming numbers may eventually spark more clusters, further worsening the situation.

As Kucharski put it, a relatively quiet period can hide how quickly things can tip over into large outbreaks and how a few chained amplification events can rapidly turn a seemingly under-control situation into a disaster. We're often told that if Rt, the real-time measure of the average spread, is above one, the pandemic is growing, and that below one, it's dying out. That may be true for an epidemic that is not overdispersed, and while an Rt below one is certainly good, it's misleading to take too much comfort from a low Rt when just a few events can reignite massive numbers. No country should forget South Korea's Patient 31.

That said, overdispersion is also a cause for hope, as South Korea's aggressive and successful response to that outbreak—with a massive testing, tracing, and isolating regime—shows. Since then, South Korea has also been practicing sustained vigilance, and has demonstrated the importance of backward tracing. When a series of clusters linked to nightclubs broke out in Seoul recently, health authorities aggressively traced and tested tens of thousands of people *linked to the venues,* regardless of their interactions with the index case, six feet apart or not—a sensible response, given that we know the pathogen is airborne.

Perhaps one of the most interesting cases has been Japan, a country with middling luck that got hit early on and followed what appeared to be an unconventional model, not deploying mass testing and never fully shutting down. By the end of March, influential economists were publishing reports with dire warnings, predicting overloads in the hospital system and huge spikes in deaths. The predicted catastrophe never came to be, however, and although the country faced some future waves, there was never a large spike in deaths despite its aging population, uninterrupted use of mass transportation, dense cities, and lack of a formal lockdown.

It's not that Japan was better situated than the United States in the beginning. Similar to the United States and Europe, Oshitani told me, Japan did not initially have the PCR capacity to do widespread testing. Nor could it impose a full lockdown or strict stay-at-home orders; even if that had been desirable, it would not have been legally possible in Japan.

Oshitani told me that in Japan, they had noticed the overdispersion characteristics of Covid-19 as early as February, and thus created a strategy focusing mostly on cluster-busting, which tries to prevent one cluster from igniting another. Oshitani said he believes that "the chain of transmission cannot be sustained without a chain of clusters or a megacluster." Japan thus carried out a cluster-busting approach, including undertaking aggressive backward tracing to uncover clusters. Japan also focused on ventilation, counseling its population to avoid places where the three C's come together—crowds in closed spaces in close contact, especially if there's talking or singing—bringing together the science of overdispersion with the recognition of airborne aerosol transmission, as well as presymptomatic and asymptomatic transmission.

Oshitani contrasts the Japanese strategy, nailing almost every important feature of the pandemic early on, with the Western response, trying to eliminate the disease "one by one" when that's not necessarily the main way it spreads. Indeed, Japan got its cases down, but kept up its vigilance: when the government started noticing an uptick in community cases, it initiated a state of emergency in April and tried hard to incentivize the kinds of businesses that could lead to super-spreading events, such as theaters, music venues, and sports stadiums, to close down temporarily. Now schools are back in session in person, and even stadiums are open—but without chanting.

It's not always the restrictiveness of the rules, but whether they target the right dangers. As Morris put it, "Japan's commitment to 'cluster-busting' allowed it to achieve impressive mitigation with judiciously chosen restrictions. Countries that have ignored super-spreading have risked getting the worst of both worlds: burdensome restrictions that fail to achieve substantial mitigation. The United Kingdom's recent decision to limit outdoor gatherings to six people while allowing pubs and bars to remain open is just one of many such examples."

Could we get back to a much more normal life by focusing on limiting the conditions for super-spreading events, aggressively engaging in cluster-busting, and deploying cheap, rapid mass tests —that is, once we get our case numbers down to low enough numbers to carry out such a strategy? (Many places with low community transmission could start immediately.) Once we look for and see the forest, it becomes easier to find our way out.

ROXANNE KHAMSI

They Say Coronavirus Isn't Airborne—but It's Definitely Borne by Air

FROM *Wired*

Amid the hourly updates on the new coronavirus, a single, calming fact stands out: a particle of happy news, hanging in a cloud of dread. The germ that causes Covid-19 may be responsible for a terrifying public health disaster, but hallelujah, thank the lord, *at least it isn't airborne.*

This message is now dogma for news outlets and public health officials. They impress on us that droplets laced with the new coronavirus don't remain aloft for long—that they only sail for six feet at the most before they fall onto the ground. That's why we're told that soap and water are the best protections one can find: twenty seconds' worth of hand-related hygiene, repeated many times throughout the day. *The virus isn't airborne;* so keep on washing when you can. *The virus isn't airborne;* so you'd be wise to trade your grubby handshake for an elbow bump. *The virus isn't airborne;* so don't forget to keep your fingers off your face.

But I'm afraid this standard line—this single, calming fact about the new coronavirus—may not be as simple as it seems. When health officials say the pathogen isn't "airborne," they're relying on a narrow definition of the term, and one that's been disputed by some leading scholars of viral transmission through the air. If these scholars' fears bear out—if the new coronavirus does, in fact, have the potential to travel farther through the air than officials have been saying—then we might need to reevaluate our standards for protecting health care workers at the front lines of fighting Covid-19. In fact, we might need to make some tweaks to all our public health advice.

From early on, any spread of the new virus through the air has been downplayed from the top. World Health Organization director-general Tedros Adhanom Ghebreyesus assured people on Twitter last week that "actually it's not airborne." He went on to clarify that "[i]t spreads from person to person through small droplets from the nose or mouth which are spread when a person with #COVID19 coughs or exhales." According to this way of thinking, the blobs of viral particles that get expelled from coughs and exhales are too big to float around; so they mainly cause infection by landing onto someone close, or by dropping on a surface from which they're later transferred to someone's body via touch.

For public health officials such as Tedros (who goes by his first name), a *truly* airborne virus is one that floats around for extended periods—like measles, which is known to be infectious in the air for at least half an hour. A pathogen like this can create a nightmare scenario. A sick person might ride an elevator, for instance, and shed some virus along the way. Later on, someone else who got into the same elevator might breathe in those germs and develop the disease.

There are very good reasons to believe—and good reasons for public health officials to assure the public—that the new coronavirus virus isn't "airborne" in that specific and apocalyptic sense. But the definition used by these officials may also be obscuring vital details of transmission. In particular, it papers over all the nuances in how someone's virus-laden cough or sneeze or breath really travels through the air. The authorities employ a rule of thumb for distinguishing what they call "droplets" from "aerosols." Droplets are often defined as being larger than five microns in diameter, and forming a direct spray that is propelled by cough or sneeze up to two meters away from the source patient. Aerosols, in this scenario, are smaller gobs of potentially biohazardous material that may remain afloat for longer distances.

This black-and-white division between droplets and aerosols doesn't sit well with researchers who spend their lives studying the intricate patterns of airborne viral transmission. The five-micron cutoff is arbitrary and ill advised, according to Lydia Bourouiba, whose lab at the Massachusetts Institute of Technology focuses on how fluid dynamics influence the spread of pathogens. "This creates confusion," she says. First of all, it garbles terminology. Strictly speaking, the aerosols are droplets too. When you breathe out or cough, you release bits of watery mucus from inside your body in a wide array of sizes, ranging from bigger, wetter ones to finer ones. All of these are *droplets*. The smallest droplets are commonly described as *aerosols*. Whatever you call them, though, any of these bits of mucus may be laced with viral pathogens. To make matters more complicated, when the water component of droplets dries up in the air, the remaining bits of floating virus are called "droplet nuclei," which are even lighter and more apt to travel long distances. Aside from size, other factors, such as local humidity and any drafts of air, will also affect how far a droplet flies.

Even the fattest droplets may not always fall right to the ground within a few feet. When you go to the ocean on a windy day and feel the sea spray on your face, you've just encountered droplets of a size that might be described as "not airborne" in a public health briefing. Even breezes that are far more subtle than the ones coming off the ocean can lift and push a droplet. Oddly, though, many traditional studies of droplet trajectories have made use of simplified models that don't account for the gust of air released when a person coughs or sneezes, which gives those droplets an extra push. Bourouiba calls this a mistake. Her lab has found that coughs and sneezes, which they call "violent expiratory events," force out a cloud of air that carries droplets of various sizes much farther than they would go otherwise. Whereas previous modeling might have suggested that five-micron droplets can travel only a meter or two—as we've heard about the new coronavirus—her work suggests these same droplets can travel up to eight meters when taking into account the gaseous form of a cough.

For researchers like Bourouiba, who study the physics of pathogens' paths, any virus traveling in the air might as well be described as "airborne." But there is no consensus among scientists as to which pathogens should get that label and which shouldn't. Julian Tang, a virologist at the University of Leicester in England, co-authored a review article on this very topic last year. The paper noted that for some researchers, "airborne transmission" involves only fine aerosols. For others, it can involve both aerosols and larger droplets. Ultimately, in their paper, Tang and his colleagues settled on using the phrase to mean transmission by particles of fewer than ten microns in diameter—a cutoff twice as large as what the WHO has used.

The debate over whether something is "airborne" is particularly sensitive around pathogens that cause the most acute, deadliest outbreaks. But there's not even agreement among experts as to how regular old influenza transmits through the air. Those who say the flu does this well point to a curious incident from the 1970s in which an airplane with fifty-four passengers was grounded on the tarmac for three hours because of engine issues during a take-off attempt. There was one person who had been ill onboard; and within three days, three-quarters of the other people who had been on the plane showed symptoms of flu such as cough, fever, and fatigue. The majority of those tested were positive for the virus. Donald Milton, whose research at the University of Maryland School of Public Health includes studies of infectious bioaerosols, says that all these years later he and his peers are still trying to convince other scientists that influenza is substantially airborne. He published a paper in 2018 asserting that, contrary to what some might think, sneezing and coughing are not required for influenza virus to be released in an aerosol form that can float around.

Meanwhile, the aerodynamics of more exotic pathogens have stirred controversy. One infectious-disease expert warned, in 2014, that Ebola might become highly transmissible by air. This proved to be a false alarm. There is some evidence that coronaviruses such as SARS and MERS can travel in hospital air. Some researchers still dispute these data: the MERS research, for example, did not use a hospital room without infectious patients as a control. But others take it as a given that these coronaviruses were floating in their infectious form around parts of hospitals.

As for the airborne behavior of the new coronavirus, scientists are racing to obtain data. A study published in the *Journal of the American Medical Association* on March 4 looked at the hospital isolation rooms of three patients in Singapore with Covid-19. The study offered some solace because it didn't find evidence of the virus in air samples. However, the air vent blades in one patient's room did test positive. A second study, described in a preprint paper published on March 10, examined the hospital environments of Covid-19 patients in Wuhan, China. Although the levels of the microbe that causes Covid-19 in most rooms were undetectable or low, the study did find the presence of the virus in aerosol form.

That there would be non-negligible amounts of virus in the air does not surprise Linsey Marr, a researcher at Virginia Tech who studies the dynamics of viruses in the air. "This is exactly what I suspected," she says. Even before that paper came out, she'd told me it's "unfortunate" that the WHO insists on saying that the new coronavirus "is not airborne."

Crucially, the hospital studies only looked for the genetic signature of the virus, as opposed to mixing the viral material with animal cells to see whether it would wreak havoc. As such they could not know whether the viral material present in the ventilation system or the air was infectious. This is a critical point—virologists emphasize that the presence of residual RNA or DNA left by pathogens in no way guarantees that people might get sick from it. However, the question of whether the new coronavirus is infectious as an aerosol was explored in another paper posted as a preprint this week. In that study, scientists used a laboratory machine to force the virus into aerosolized form and then tracked it for three hours. They found the pathogen was still able to infect animal cells at the end of that time frame, although there was substantially less virus suspended in the air from one hour to the next.

These three new papers should not be overinterpreted. Only one of them has been vetted by peer review at this point. It also remains unclear, and undemonstrated, whether the Covid-19 virus released from patients' lungs comes out in aerosol form; whether aerosolized particles of this virus travel significant distances; and, if so, whether they do so in sufficient number to cause infection. Notably, while the joint WHO-China mission report published in late February said that although airborne particles were "not believed to be a major driver of transmission," it noted that such a mode "can be envisaged if certain aerosol-generating procedures are conducted in health care facilities."

Given that much research on airborne transmission in outbreaks is focused on medical settings, it's also less than clear how even the most common viruses might pass from person to person under everyday circumstances. Julian Tang and his colleagues have created a visualization of the breaths exchanged by two people in conversation standing three feet apart. Most of the time, the puffs of air they let out remain separate; but portions of their exhalations do sneak from each person's breathing space into the other's. Given all this uncertainty, some experts say there needs to be better public messaging on the spread of the new coronavirus. "Crowded public transport where people can breathe on each other may also lead to transmission of infection," Tang says, echoing public health advice that, while widespread, may not be getting as much emphasis as hand-washing. Milton agrees, adding that it might be wise to shut off air-recirculation systems in cars, which could potentially spread the pathogen among passengers.

Even if it turns out that the new coronavirus is meaningfully airborne, at least in rare circumstances, you shouldn't rush out to buy masks, including N95 respirators. Don't do that. We've already witnessed grave shortages of masks for health workers and people who are immunocompromised. To buy one now is to put those people's lives in danger.

The scientists I spoke with for this story do not want people to shutter themselves inside in fear of toxic vapors. They point out that being outdoors, in fresh air exposed to UV light, is healthy. They do not want to encourage anyone to cower from all social interaction. This article is not meant to induce panic among the worried well, who clog health systems needed for people who are actually ill. But there needs to be a more nuanced understanding of this issue.

When public health officials say a pathogen is or isn't "airborne," they create a false dichotomy that doesn't keep people safe. In this particular case, the folks who are most at risk for airborne transmission are medical workers. Just this week, amidst concerns about insufficient supplies of respirators, the U.S. Centers for Disease Control and Prevention updated its guidance for health care personnel dealing with the Covid-19 pandemic. Based on its assertion that "airborne transmission from person-to-person over long distances is unlikely," the agency said that "facemasks" —presumably the floppy surgical masks that do not do as much to protect against floating pathogens—constitute an acceptable alternative for health care workers. (It does note that N95s should be prioritized for procedures that are especially likely to release virus into the air.) But if the *JAMA* study and preprint articles from this week prove correct, and the new coronavirus falls somewhere on the spectrum of airborne-ness besides *not at all,* then this advice might be counterproductive.

When it comes to this virus's ability to travel in air—in hospitals or elsewhere—it's hard to know where things will ultimately land. Until then, describing it in absolute terms seems risky.

AMANDA MULL

The Difference Between Feeling Safe and Being Safe

FROM *The Atlantic*

ON A NORMAL DAY, the White House is one of the safest buildings in the world. Secret Service snipers stand guard on the roof, their aim tested monthly to ensure their accuracy up to 1,000 feet. Their heavily armed colleagues patrol the ground below and staff security checkpoints. Belgian Malinois guard dogs lie in wait for anyone who manages to jump the property's massive iron fence.

But safety means something different in a pandemic. Over the past few days, several aides to Vice President Mike Pence, including his chief of staff, have tested positive for the coronavirus. The outbreak is the second in the White House in a month, after dozens of people, including President Donald Trump himself, tested positive following the apparent super-spreader event hosted by the administration to celebrate the Supreme Court nominee Amy Coney Barrett.

The outbreaks have been both utterly predictable and totally shocking. The Trump administration has consistently downplayed the severity of the coronavirus, encouraged Americans to resist safety measures, and promised that the pandemic is nearing its end. But the people orchestrating the country's disastrous coronavirus response had no plausible deniability: the very best experts, information, and precautions were all available to them, even if they refused to pass that help on to others.

People will write books on everything Donald Trump did wrong during the pandemic, with explanations both personal and ideological for his administration's often willful failures. But for a group of people for whom self-preservation has long been an obvious goal, their willingness to put themselves in optional danger, given all the resources at their disposal, can't be completely explained by Trump's lack of empathy or his advisers' policy goals. It suggests that on top of everything else, the administration fell prey to an error of intuition: presumably, Trump and his coterie felt safe, despite the mortal danger nipping at their heels for all to see.

Trumpworld's infection fiasco is an especially bizarre case study of one of the pandemic's defining features: how different *feeling* safe and *being* safe actually are. This misperception has played out in millions of homes and workplaces across the country as regular people make good-faith efforts to grapple with the swiftly changing circumstances of American life, absent the resources available to the federal government. Things that used to be safe, such as visiting grandparents and attending a friend's wedding, are now potentially deadly. Things that used to be foreboding, such as the sight of many masked strangers in public, are now a source of comfort.

This new sort of safety is difficult to adapt to, both practically and emotionally. Over the summer, previously innocuous private social gatherings, such as dinner parties and birthday celebrations, were cited as a primary driver of new infections all over the United States. In some instances, the people involved perhaps didn't care about the risk or thought the pandemic was fake. But in others, they likely couldn't imagine why they should be scared of time with loved ones. Many of these same people were wearing masks to the grocery store, using hand sanitizer, and otherwise doing what they understood to be asked of them.

Safety is among the most powerful motivators of human behavior, which also makes the drive to feel safe a potent accelerant for confusion, disinformation, and panic. Staying safe requires an accurate, mutually agreed-upon understanding of reality on which to assess threats and base decisions. Since the pandemic arrived in the United States, however, politicians have sparred over basic safety precautions and aggressive reopenings. The federal government and many of its allies at the state and local levels have actively undermined efforts to get people on the same page. These contradictions have sown confusion, even among those who disagree po-