INTRODUCTION

In life, we all have a moment when we wake up to a bigger picture. For Ann Hodges, that moment arrived on November 30, 1954, at precisely 1:46 p.m., while she was lying on the couch. It wasn't so much an epiphany as a painful reality that struck her that day, when a lime-green "cosmic missile" streaked across the clear afternoon sky, crashed through her roof, bounced off a console radio, and flew smack into the side of her body.

As the only known person to be hit by a meteorite, Ann became an instant sensation. By nightfall, hundreds of people, including the national news media, descended upon her backyard, snapping photos of the extraterrestrial object, checking out the damage to her house, and looking in awe and horror at the jet-black, football-sized bruise the impact left on her hip.

Because she was napping, Ann had slept through the fireball's spectacular descent. Witnesses saw it blaze across three states; TVs began scrambling from the alien interference; and the sonic boom jolted a boy right off his bike more than one hundred kilometres away, in Montgomery, Alabama. As for the locals, when the shooting star finally hit ground zero in the town of Sylacauga, most of them thought they'd heard a plane crash or an exploding bomb.

After a few weeks, though, as with all freak accidents, the buzz died down. The reporters packed up and went home and the neighbours returned to their daily lives. And while the meteorite

certainly made an impression on everyone that day, only one person's cosmic perspective was forever changed. For Ann Hodges, the universe, with its meteors and comet showers and supernovas, was no longer a separate place somewhere "out there." Oh, no. The cosmos could come right into your house, if it wanted to, and slap you wide awake.

FAR FROM BEING IDYLLIC and tranquil, the heavens are hell. You've got your raging flames, your choking plumes of poisonous gas; darkness, chaos, and violent destruction are pretty much everywhere. In fact, if you look up into the sky tonight in the direction of Sagittarius, just above the archer's arrow, there's a supermassive black hole in our galaxy that is, at this very moment, obliterating everything within its horizon.

That's the universe we live in. But it's not the way it *feels*. That you and I are relatively calm right now, that we aren't in a raw panic at the total and utter mayhem that dangles right above our heads, is because we live in a bubble, a physical one called the atmosphere. From space, this dome is clearly visible. It's a thin, bluish-white film that acts like a planetary force field: it blocks out lethal radiation, maintains temperatures within a tiny range (compared to the extremes of space), and incinerates most of the meteors that would otherwise pulverize the surface of Earth.

As human beings, we all live inside another kind of bubble as well: a psychological one that shapes our ideas about the everyday world. This is our "reality bubble." Just as rocks hurtling at supersonic speed find it hard to penetrate Earth's atmosphere, unwelcome facts and unfamiliar ideas almost never make it through the membrane of the reality bubble. It shields us from thinking about forces "out there" that are seemingly beyond our control and lets us get on with the business of our lives.

But problems arise with inflated certainty, and we see it over

and over again. Whether it's real estate bubbles, or stock market bubbles, or political bubbles, being in a bubble means, by definition, that we've got a warped perception of reality. And in the end, all bubbles share the same fate: inevitably, they burst.

So we might do well to remember that even our most stable conceptions of the world can be overturned. For over two centuries, the universe was understood to be governed by Newtonian physics, and then Einstein came along. But it doesn't always take a genius to expand our view of the world. Sometimes it just happens. For Ann Hodges, it happened when a meteorite torpedoed through her ceiling one afternoon. And for you, it may just be the book that you're holding in your hands right now.

HUMANS HAVE A TENDENCY to think we have an accurate picture of the world, but often we're wrong. That's because every person is born with a blind spot. In fact, we have two: one in each eye. In the same way that you would be unable to see all of the movie screen if you were given a crummy seat behind the projector at a theatre, situated at the back of your eyeballs there's an area where light receptors do not grow, because it's the exact spot where the optic nerve jacks into your brain. And yet, despite the fact that the area it eclipses is relatively large (nine full moons in the sky could fit in this broken field of view), most of us never even notice it.

The best way to *see* what you cannot see is with your own eyes. So let's take a look. Cover your left eye and use your right eye to look at the dot above. Now, with your eye still trained on the

dot—staying aware of the cross but not focused on it—begin to move your head slowly towards and away from the book. You should notice that at a certain point the cross suddenly vanishes; it disappears from sight. Remarkably, this blank spot doesn't register as some sort of void. Instead, our brain compensates for the emptiness, and with our own perceptual version of Photoshop it even fills in the right background colour. Our blind spots are perfectly camouflaged. We are blind to our blindness.

Now, you might think that a blind spot this obvious would have been detected long ago, but it wasn't until a French physicist named Edme Mariotte was dissecting an eye and came across the bundle of nerves connected to the retina, that he wondered if it might be blocking our sight. Doing some vision tests with his own eyesight, he discovered what was soon to become a mini-sensation in the 1600s. It delighted the nobles of the royal court, who revelled in the magic trick of making each other disappear without blinking an eye. Legend has it that across the Channel, King Charles II would play this visual trick with his prisoners, visually decapitating them with his mind's eye before later executing them in real life.

Of course, blind spots are not only *in* our eyes; they are also in our surroundings. The French for "blind spot" (*angle mort* or death angle) says it all: every year in the United States alone, 840,000 car accidents happen because we can't see something very large driving at us until it crashes into our field of view.

THE PHILOSOPHER LUDWIG WITTGENSTEIN once said that "the aspects of things that are most important for us are hidden because of their simplicity and familiarity." Put another way, we often can't see what's right in front of our noses. We've all experienced it: looking everywhere for your keys when they are staring right at you from the kitchen counter.

Individually, we can be blind to the obvious, but collectively, as a society, we can be blind as well. Here's a curious fact to consider: in the twenty-first century, there are cameras *everywhere*, except where our food comes from, where our energy comes from, and where our waste goes. How is it, then, that the most powerful species on the planet is blind to how it survives?

You might say that modern humans interface with nature as though we live in a bubble. It's the reason why, in the United Kingdom, one in three young adults don't know that eggs come from chickens, a third of children believe that cheese comes from plants, and a whopping 40 percent of youth have no idea that milk comes from cows. For these kids, food comes from where you'd think it comes from: "Duh," the supermarket.

Now, it's not the case that young people aren't smart; it's just that their focus has shifted. The average child in the United States spends forty-five hours a week looking at electronic media and only half an hour of unregulated time outdoors. That being the case, we shouldn't be surprised that the cultural world fogs over the natural one. Immersed in this environment, the average American kid is able to recognize one thousand corporate logos but can't name ten plants or animals native to the area in which they live.

Adults don't fare much better. From inside the bubble, the origin of our greatest source of energy—the fuel that powers our global economy—is also a big unknown. If you take a moment to ask around, you'll soon discover that the average person has no idea what oil is. The liquid we pump into our gas tanks to get to work doesn't come from the pulp of dinosaurs, but every tank of gas *is* powered by a thousand tons of ancient life. So which dead species fuel our daily commute? And what caused those giant graveyards that pressure-cooked into the rich black oil fields we drill for energy?

Finally, we are exceptionally blind to what we waste. From excrement to trash to toxic waste, we live with the illusion that refuse can be made to disappear or, with the push of a button, be magically flushed away. That our waste goes somewhere, that our own pollution finds its way right back into the food we eat, the water we drink, and the air we breathe, is one of the reasons the human race is in such deep shit today.

The kicker is our ignorance as a species would be a lot easier to write off if we weren't also so intelligent. After all, we are the smartest animals on Earth. We are the primates with superpowers. We can fly at the speed of sound and communicate across the planet at the speed of light. Our species has figured out how to hack DNA and change the very codes that govern life.

But the problem is that *life* is disappearing.

Scientists tell us we are currently in the midst of the sixth great extinction. On land, from armadillos to zebras, animal populations are plummeting. In the sea, fish stocks are crashing and coral reefs are bleaching. Glaciers are melting. Droughts are increasing. Wildfires are raging. The population is exploding and the climate is changing. The creep of catastrophe nears day by day, and yet when we reach out our arms . . . it is only to take another selfie.

That somewhere in the back of our minds we know civilization is teetering on the brink explains our cultural obsession with the zombie apocalypse. These dark fantasies don't come from nowhere. We all know that things are going very wrong, but living in a bubble means that, for now, we get to ignore it. Instead, we playfully channel our collective unease, mocking our own fear of a seemingly imminent societal crash. From TV shows to survival guides, we "joke" about building bunkers and stockpiling weapons and food supplies. In cities around the world, tens of thousands gather in "zombie walks" dressed in

ghoulish makeup and rags, limping along in a low-rumble chant for one, singular desire.

And what is it that the zombies want? The zombies want *braaaains*.

It's worth asking whether we could fend for ourselves if there were no societal means for survival. Because when you think about it, our system of society works precisely because we conform to it, like brainless zombies. The human population is almost eight billion strong, marching to a capitalist drumbeat of *eat, work, shop, and sleep*. Now, it might be one thing if we loved it, but we don't. I mean, seriously, have you ever met anyone in your life who loves the rat race?

So, given that humanity faces dire consequences *and* that most of us don't even like what we do, the question is: Why do we do it?

The big myth, I will argue, is that we are brought up believing there is no other way. We are simply told that this is how the system works. But what if there is another way? What if this "real world" we're so invested in isn't that real at all? What if we could scrub away the fog of humanity's biggest blind spots so we can see more clearly and begin to uncover what is beyond our reality bubble?

Proust famously said, "The real voyage of discovery consists not in seeking new landscapes but in having new eyes." And so our journey must begin right where we are: by seeing the ordinary, everyday world we live in, in an extraordinary new way.

IN JOHN CARPENTER'S 1988 cult classic sci-fi movie *They Live*, a drifter named John Nada gets hold of a pair of special sunglasses that reveal "truths" that ordinary citizens can't see. Putting them on and looking at magazine ads, billboards, or the TV, he sees

their real messages: to obey, consume, conform, and stay asleep.

As a modern parable, the film struck a chord. Its influence can be seen in films, video games, and street art, like Shepard Fairey's Obey series, and in Hal Hefner's political posters and web memes. The film's secret conceit is this: if only a pair of glasses like this existed, people might begin to question why reality is not what it seems.

Luckily, something like that *does* exist.

In this book, we will venture into the unseen world around us, but instead of fictional sunglasses we will be using scientific lenses to bring hidden views to light. That's because scientific instruments are, in a very real way, our new eyes, giving us superhuman abilities to see and hear well beyond what our senses perceive.

On true crime shows, we often catch a glimpse of what modern science can reveal. A nice, tidy living room might appear perfectly ordinary to the naked eye, but once investigators have sprayed luminol—a chemical that reacts with iron in hemoglobin—and flicked off the lights, the chemical's neon-blue glow illuminates blood splatters on the wall, revealing a grisly crime scene.

We have a tendency to think that seeing is believing, but there is so much that we don't see unaided. The same is true for the world around us. Our vision is feeble compared with the most advanced scientific tools. Telescopes allow us to see galaxies over thirteen billion light years away, and using electron microscopes, we can zoom right down to the atomic level to see and touch the very building blocks of our universe.

In the pages ahead then, reality will at times seem bizarre and disorienting. Like falling down a rabbit hole into Wonderland. We will shrink in size, grow into giants, and even find ourselves understanding the languages of other animals. Applying this scientific lens to the world around us radically alters our old ideas about the world, allowing us to question what surrounds us, what sustains us, and, perhaps most importantly, what controls us.

AS A SCIENCE BROADCASTER and journalist, I have spent more than a decade interviewing and learning from the world's top scientists and thinkers. One of the great advantages of working with scientists from many different fascinating fields is that it has given me a broad spectrum of scientific knowledge to draw from, allowing me to share and communicate expertise from a wide range of disciplines. These different disciplines are like pieces in a puzzle. Individually, each gives us a clue as to what's going on, but only by putting them together can we see the bigger picture.

And now more than ever, we need to see clearly, because we are at a critical juncture in human history. Our species is locked on a deadly collision course, one that threatens to extinguish life on Earth precisely because our vision of reality is incompatible with scientific truth. Instead, what we call "common sense" thinking has blinded us for far too long.

In this book, we will examine ten of humanity's biggest blind spots. Section One begins with an introduction to the blind spots we are born with as individuals, and reveals how science and technology allow us to see beyond our biological limits. With this new form of sight, we will journey through the everyday world to uncover what our own eyes are unable to perceive.

In Section Two, we will look at our collective blind spots and investigate how as a society we engage in willful blindness. We'll focus on the most critical aspects of our basic biology—our food, energy, and waste—and see how science has radically transformed the support system our lives depend on, and engineered a world that to the average person is almost entirely opaque.

Finally, in Section Three, we will examine intergenerational blind spots. These are ways of thinking about the world that seem natural or inevitable but are in fact inherited world views passed on from generation to generation. Here we will examine how we navigate the grand dimensions of time and space like the proverbial fish that knows not the water in which it swims.

Carl Sagan once said that "our species needs, and deserves, a citizenry with minds wide awake and a basic understanding of how the world works." This book is a humble effort to respond to that need. So let us begin.

PART ONE

BIOLOGICAL BLIND SPOTS

WHAT SURROUNDS US

1
THE OPEN JAR

Where the telescope ends, the microscope begins.
Which of the two has the grander view?
—VICTOR HUGO

In the blink of an eye, Dondidier was gone, but his disappearance was not a part of the circus act. As the *Hamilton Daily Times* reported on August 16, 1913, detectives and sniffer dogs were quickly dispatched to track down the performer, who vanished two days before opening night. Fortunately, the show was not called off. By Friday evening, the acrobat was spotted by a crew member, hiding inside the main tent. And while the fiasco made the headlines, for the public, the real story was not his mysterious return, it was his worth. The circus star was valued

at $500, which, in today's money is more than $12,000; a preposterous amount by all accounts, since Dondidier was just a flea.

A century before the bright lights of Hollywood, the greatest show on earth was tiny: it was the flea circus. The little top was an international sensation, and in cities like New York, Paris, and London, crowds came from afar to watch the parasites perform. There were the ballerina fleas, the sword-fighting fleas, the cannonball fleas, the strongman fleas, the tightrope walkers, the tango dancers, and the trapeze artists. It was here, dazzled by their miniature feats of daring, that audiences applauded the most reviled creature of them all: *Pulex irritans*, the bloodthirsty, plague-carrying, human flea, had catapulted into the spotlight and become a star.

The popularity of the flea circus came, in part, from its well-guarded secret. The big question being: How do you train a flea? Plucked quite literally from the casting couch, the insects were skilled fugitives and could easily hop off the stage and escape. So, when pressed, the flea trainers, or "professors" as they were formally known, revealed a trick for taming the tiny beasts: to keep the animals under control at all times, they held them in an invisible prison.

To do this, the fleas were dropped into a small glass jar and carefully sealed inside. As wingless pests that evolved to leap onto their hosts for a blood meal, fleas have spring-loaded legs that let them jump over one hundred times their own height and the endurance to keep bouncing over thirty thousand times. But inside the jar, their athletic prowess worked against them, because as the fleas shot skyward, they smacked their bodies hard, and repeatedly, up against the lid.

But soon—to avoid the pain—the fleas learned; instead of jumping high, they jumped lower so they no longer ricocheted off the top. At this point, according to the professors, you could leave the lid off forever and the pests would never escape. For the fleas, freedom was only a bounce away, but the trap had been set in their minds.

The story was good. Good enough to fend off the curious—but it also wasn't true. And while flea training may yet hold a lesson for *human* society, it was completely lost on the fleas. That's because behind the scenes, as the "professors" knew full well, the bloodsuckers could not be trained; that if you put a flea inside a jar and remove the lid, a flea, of course, will flee.

But peering through magnifying glasses, eyewitnesses swore that they saw the fleas dancing and juggling at their master's bidding. So the question remains: how did the insects perform the incredible stunts? It turns out, the cheerful spectacle had a dark side. For the fleas, it was torture.

Dressed in pink tutus and glued to tiny parasols, the insects were not willing participants. The gold wire leashes that they wore were harnesses that were used to subject them to noxious conditions. "Soccer-playing" fleas, for instance, played with a tiny cotton ball soaked in citronella, which was repulsive enough to them that they kicked it away on contact. The "jugglers," on the other hand, were held on their backs with glue and the motion of their legs rolled a lint ball above them. As for the musicians in the flea "orchestra," they were tied down to seats on a music box, each with a miniature instrument stuck to its forelegs. Then, with a little tap on the head to each—or sometimes, more sadistically, with a flame lit beneath—they'd begin flailing their free legs about, giving the appearance of waving to the music.

Now before we cue the tiny violin, we should be reminded that to the average person, one flea's life is worthless. Even a hundred lives, or a hundred thousand. We wouldn't blink at a global flea Armageddon; we'd be pleased to be rid of them. But strangely, when people today see "strongman" fleas on YouTube pulling tiny carts, or "acrobat" fleas walking tightropes; when they are onscreen at a scale we can interact with, magnified like micro movie stars, the reaction to these pests changes: *You're hurting the fleas! The leashes are strangling them! This is animal cruelty!*

Keep in mind, in their own homes, chances are these people would crush a flea dead in an instant and fumigate for good measure.

Here's the thing: as giants, human beings have a tendency to treat small life as though it's insignificant. As flea expert and entomologist Tim Cockerill has observed: "Sometimes, in a city like London, you'll see the tiniest speck flying across the room or landing on the table, or in your beer at the pub, and most people don't think of this as a life. They'll just pick it out and flick it away, like it's a bit of dust or soot or whatever, but that's actual animal diversity. If you take a moment to look at that speck, it opens up a whole new world."

And it's true. In fact, whole new species have been discovered in this way.[1]

ROBERT HOOKE WAS AN INTELLECTUAL GIANT, but crippled with scoliosis and Pott's disease, he was also a hunchback. Regarded by some as the Leonardo da Vinci of England, he made a staggering number of contributions in the fields of astronomy, biology, physics, paleontology, and even architecture. Early on, he developed the wave theory of light, proved the existence of air, defined the limits of human vision, discovered and named the cell, deduced that fossils were the remains of once-living things, and proposed the idea, inconceivable at the time, that species could disappear through extinction. But today, he is best known for one iconic drawing: a magnified illustration of a flea.

Folding out over four pages, and "depicted with the anatomical precision of a rhinoceros," as Oxford historian Allan Chapman wrote, the magnified beast was a centrefold from Hooke's 1665 bestseller, *Micrographia*. And while Hooke's notoriously difficult

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1 Tim Cockerill discovered a new species of parasitic wasp when it "committed suicide" and fell into his cup of tea one day.

personality made him unpopular with fellow academics,[2] his book at least made him very popular with the public. In it, he presented the wonders of the magnified world: illustrations of bee stingers, fly's feet, snail's teeth (they have over twenty thousand of them), and even mites in cheese. The detail of the pictures would still baffle most today, but for people introduced to these "minute bodies" for the very first time, the book was nothing short of mind-blowing.

Because of *Micrographia*, the flea was elevated to a microscopic muse. And inspired by Hooke's illustrations another man set his sights on delving even deeper into the world of the minuscule. Grinding finer and finer lenses until his vision was magnified over 270 times,[3] Antonie van Leeuwenhoek was a contemporary of Hooke's whose powerful homemade microscopes were so good they landed him the title of "father" of a new field: microbiology.

With the ability to zoom into the level of a micron, or one-millionth of a metre, Van Leeuwenhoek was able to see well beyond the capacity of the naked eye. And so it was that one day, while examining a few drops of rainwater that had collected in a pot, he made an earth-shattering discovery. Wiggling beneath his eyes, at a stupendously small scale, were little creatures swimming through the liquid. They were smaller than anything he had ever seen. He named them *animalcules*.

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2 You've likely heard Newton's famous quote: "If I have seen further than others, it is by standing on the shoulders of *giants*." (emphasis mine) It's often cited as a reminder of the power of humility. Except, some scholars today believe it may have been the 17th century version of throwing academic shade. It came from a letter written by Newton to Hooke in which they were embroiled in a scientific feud over credit in the field of optics. And Hooke, it should be noted, was short.

3 Based on his drawings, Van Leeuwenhoek is thought to have made some instruments that could magnify objects up to 500 times.

It's important to keep in mind that what we call microorganisms today did not officially exist in the 1600s. Van Leeuwenhoek was the first to access a world that was previously invisible to the human eye. So when in 1673 he began documenting his findings in a series of letters to the Royal Society in London, leading scientists of the day weren't just skeptical, they thought he was either hallucinating or possibly insane.

What Van Leeuwenhoek had on his side, however, was that he was prolific. And as he began looking closely at everyday things, they transformed into magnified wonders. In 1673, he focused his lens on the life force moving through all of us by putting a drop of his own blood under the microscope. The liquid, it turned out, contained solids: flowing through our veins he saw blood cells, which he described as concave "globules."

In 1677, he spied an entirely new life form and discovered protozoa. Creatures "so small, in my sight, that I judged that even if 100 of these very wee animals lay stretched out one against another, they could not reach to the length of a grain of coarse sand." That same year, he made his greatest personal discovery when he examined another body fluid, his own ejaculate. He became the first person to witness living sperm cells, magnified and "moving like a snake or like an eel swimming in water."

Writing to the Royal Society on September 17, 1683, Van Leeuwenhoek had turned his detective work to dental hygiene. Observing the plaque, or "white matter," between his teeth, he pried opened a portal to a whole new dimension: "I then most always saw, with great wonder, that in the said matter there were many very little living animalcules, very prettily a-moving. The biggest sort . . . had a very strong and swift motion, and shot through the water (or spittle) like a pike does through the water. The second sort . . . oft-times spun round like a top . . . and these were far more in number."

There, in his mouth, he had uncovered a metropolis of life

at the most distant frontier of the microscopic world. They are still the tiniest living beings that we know of today. He had discovered bacteria.[4]

But in the scientific community, there were still strong doubts about Van Leeuwenhoek's brazen claims. In a letter to Robert Hooke, the Dutchman wrote, "I suffer many contradictions and oft-times hear it said that I do but tell fairy tales about the little animals." And so the Royal Society called upon the eminent Hooke to replicate and confirm Van Leeuwenhoek's discoveries.

Hooke had looked through a microscope before, but when he reached Van Leeuwenhoek's magnification, what he saw was baffling and "exceeded belief." And yet it was true. In his letter to the Royal Society, he reported,

> I have here sent the Testimonials of eight credible persons; some of which affirm they have seen 10000, others 30000, others 45000 little living creatures, in a quantity of water as big as a grain of Millet (92 of which go to the making up the bigness of a green Pea, or the quantity of a natural drop of water). . . . If according to some of the included testimonials there might be found in a quantity of water as big as a millet seed, no less than 45000 animalcules. It would follow that in an ordinary drop of this water there would be no less than 4140000 living creatures, which number if doubled will make 8280000 living Creatures seen in the quantity of one drop of water, which quantity I can with truth affirm I have discerned.

Under the microscope's glass lens, a tiny window had swung wide open, and the universe it revealed was gigantic.

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4 Oral bacteria are prolific: "There are 20 billion bacteria in your mouth and they reproduce every five hours. If you go 24 hours without brushing, those 20 billion become 100 billion!"

WE TEND TO FORGET that on the scale of living things we are massive. To us, reality may appear human-sized, but in truth 95 percent of all animal species are smaller than the human thumb. Even tiny animals like fleas are giants compared to the microscopic life forms that inhabit them. As the old rhyme "Siphonaptera" puts it, "Big fleas have little fleas, / Upon their backs to bite 'em, / And little fleas have lesser fleas, / And so, ad infinitum." In essence, even our pests have pests. Given that, it's worth taking a moment to consider exactly what a "pest" is. The term implies a small creature whose very existence and mode of survival is a nuisance. Fleas are only one of a vast number of species we despise. And for good reason: the rat flea notoriously served as the carrier of the *Yersinia pestis* bacterium that killed millions of people around the world, most notably in connection with the Black Death, the pandemic that peaked in Europe in the fourteenth century.[5] Because of this, some people have questioned if there is even a point to the flea's existence. As one commenter wrote online, "There are those creatures that serve no purpose whatsoever. Fleas are such an example. They don't pollinate any flowers, nor do they prey on any destructive or harmful insects. Instead, they siphon the blood of unsuspecting animals and people all the while passing harmful organisms into their bloodstream!" But the flea is not alone in being deemed "unworthy" of being alive. We hold similar attitudes towards cockroaches, mosquitoes, mites, bedbugs, wasps, ants, silverfish, spiders, flies, and many other unwelcome critters anywhere near our homes. We decide which animals should live and which should die. We divide animals into those

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5 "The flea has killed millions around the world . . . and is, indissolubly, connected with the history of Black Death. This disease in man is, in fact, caused—as demonstrated by Yersin and Simond—by the triad: bacterium (Yersinia pestis)/rat/flea (Xenopsylla cheopis)."

we admire or that benefit us—insects that are beautiful or have a "purpose," like butterflies and bees—and those we'd prefer to exterminate, especially where they compete for our food in the realm of agriculture.

As a result, we have launched our own "Black Death," a vicious chemical war against these tiny invaders. Globally, agrochemicals and pesticides have become a multi-billion-dollar industry that grows year over year.[6] But in our efforts to stamp out unwanted pests, we pour over two million metric tons of pesticides onto our plants and soils every year. Unsurprisingly, we aren't just harming the insects we don't like; we are destroying the insects we do like as well.

Scientists tell us we are witnessing a catastrophic collapse of insect populations. A German study found that on protected nature reserves, insect numbers had plummeted by 80 percent. Rodolfo Dirzo, a Stanford University ecologist, has documented a 45 percent decline worldwide in insect populations over the last four decades. And on the International Union for Conservation of Nature (IUCN) Red List, of the 3,623 invertebrates being tracked, 42 percent are under threat of extinction.[7]

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6 While pesticide manufacturers have argued that the world will face food shortages without pesticides, scientists have found that the claim is overstated, and that the majority of farms would *increase* productivity if they lowered their use of pesticides.

7 While more scientific research is required, the plummeting numbers are setting off alarms around the world. A recent study in Puerto Rico found that 98 percent of ground insects had disappeared over a period of 35 years. In the canopy, the number was 80 percent. By weight, insects typically outweigh humans seventeen times over. Without them, we can expect catastrophic consequences. That's because insects serve as the foundation of our food chain. If insects decline, a domino effect, known as a "bottom-up trophic cascade," will begin to knock out other species that rely on them.

In our desire to exterminate insects, we've lost sight of how critical they are to human survival, but the ripple effect runs right up the food chain. As British biologist Dave Goulson warns, we "are currently on course for ecological Armageddon. If we lose the insects, then everything is going to collapse." That's because insects not only help with pollination, they are nature's garbage men and recyclers as well. As Goulson notes, "Most of the fruits and vegetables we like to eat, and also things like coffee and chocolate, we wouldn't have without insects. Insects also help to break down leaves, dead trees and dead bodies of animals. They help to recycle nutrients and make them available again. If it weren't for insects, cow pats and dead bodies would build up in the landscape."

We won't be alone in feeling the effects. Already, birds that feed on insects have begun to disappear. The number of birds in Europe plunged by four hundred million in the last three decades. Some migrating songbirds, like the meadow pipit, have seen their populations decline by up to 70 percent.

We do not see it happening, and this is potentially our fatal flaw: we tend not to notice that something is disappearing until it is gone.

IN THE END, what killed the flea circus was the disappearance of its star. The little top reigned glorious for well over a hundred years but was forced to shut its tent flaps when the human flea proved no match, not for insecticides, but for the vacuum cleaner.[8] From a business standpoint, it was the cost of importing fleas that made it impractical. As Professor Tomlin, one of the last great flea trainers noted, "I have offers from all over the world to

8 *Pulex irritans* has not gone extinct. It can still be found in Greece, Iran, Madagascar, and even Arizona.

take my show, but you're afraid of one thing, when you get out of the country can you get fleas? I went to Sweden and I had to send to Majorca in Spain to get fleas every fortnight."

We have largely rid ourselves of the human flea, but our bodies continue to host many lesser-known species. Fortunately, both for them and for us, they make their livings quietly as tiny companions that we cannot feel or see. You may want to take a deep breath as you read this, but right now your face is crawling with *Demodex* mites, eight-legged arachnids whose closest relatives are spiders. One study found that by the age of eighteen, 100 percent of people tested are host to the mites.[9] Nestled in the beds of our pores and tucked into our eyelashes, the nocturnal creatures emerge each night, moving at a rate of eight to sixteen millimetres an hour, to feed and search for mates on our faces. Scientists still aren't sure exactly what they eat. It could be the sebum, or oil, our pores secrete, or they could be feasting on meals of dead skin cells or bacteria on our skin. One thing scientists do know: while these mites have mouths, they do not have anuses, and the buildup of food means that when they die they explode a flush of material from their guts, which ends up on our faces. And this fecal matter serves as a home to ever-smaller species, because hitching a ride inside the mites' guts are even more prolific life forms: bacteria.

A little face bacteria is nothing, however, when you consider that humans are *covered* head to toe in microbes. And the diversity of species is absolutely bewildering. Taking swabs from sixty subjects' bellybuttons, researchers at North Carolina State University working on the "Bellybutton Biodiversity Project" found a veritable zoo of bacteria, a total of 2,368 different species, over half of which were previously unknown to science. One person's bellybutton even housed a bacterium only known

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9 Age appears to be a factor, as babies have fewer mites.

to exist in Japanese soil. He had never set foot in Japan, so how did it get there? Well, bacteria are world travellers. Even in drawing a single breath, as microbiologist Nathan Wolfe has observed, we are sampling a safari of microbial species from around the world: "Dust from deserts in China moves across the Pacific to North America and east to Europe, eventually circling the globe. Such dust clouds harbour bacteria and viruses from the soils where they originated, as well as other microbes they pick up from the smoke of garbage fires or from the mist above the oceans they cross."

Air samples collected by scientists at Lawrence Berkeley National Laboratory found as many as 1,800 bacterial species in the air we breathe. These bacterial life forms are not just on us and around us, they are a part of us. Yale University engineers for instance, have found that a person's "mere presence" in a room adds about thirty-seven million bacteria to the mix, every single hour. What we call our own bodies are in truth only half our own. And while the myth is that bacterial cells outnumber human cells ten to one, recent research has proved that we are a little closer to par. An average human body has thirty trillion human cells and about thirty-nine trillion bacteria cells, meaning we are only slightly outnumbered, by a ratio of 1.3:1.[10]

This, of course, raises the question of who is in charge. Them or us?

In this instance, the human-microbe relationship is not so much parasitic as it is symbiotic. Despite the bad press some germs get, we've learned to live together, for the most part, in relative harmony.[11] At birth, however, we are largely

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10 Bacterial cells are much smaller than human cells—though there are a lot of them, they make up only about .2 kg of our body weight.

11 There are almost 2 billion species of bacteria, the vast majority of which are harmless to human beings.

bacteria-free[12] and acquire the majority of microscopic hitchhikers along the way in life. This is why, if you take a microbial sample from identical twins, you'll find the microbes that inhabit them have different DNA.

It's becoming apparent that *without* bacteria, our lives would be at risk, because what we call "good microbes," like probiotics, are necessary for a healthy immune system. A species known as *Bacteroides fragilis*, for instance, is found in abundance in the guts of most mammals, including 70 to 80 percent of humans. A molecule on the cell surface, called polysaccharide A, boosts regulatory T-cell production, which in turn prevents inflammation in the gut. Scientists working with mice that were specifically bred to be germ-free found them to have poorly functioning regulatory T-cells, but as soon as *B. fragilis* were introduced to their systems, their health improved and their immunity was restored.

We also call on bacteria to help us perform vital survival tasks like eating. If you're a fan of pasta, pies, or french fries, then pat your belly in thanks to *Bacteroides thetaiotaomicron*. In much the same way that cows have bacteria in their rumens that help them digest the cellulose in grasses, humans rely on *B. thetaiotaomicron* to create the enzymes that let us process starchy plant foods.

But bacteria aren't just in charge of regulating our bodies; they have bigger duties as well. As Rick Stevens, a founder of the Earth Microbiome Project, has observed, "Fifty percent of life on Earth is 'invisible' yet responsible for making the planet habitable." Scientists now know that the smallest life forms on Earth

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12 Some studies have suggested there is bacteria in the placenta, though a recent large-scale study suggests lab contamination may be the culprit. Right now, more research is needed.

are responsible for engineering planetary-scale systems, including the very air we breathe and the food we eat. And while humans walk around like we're the most powerful creatures on the planet, in reality it is the microbes that are running the show.

For starters, they produce the gas that is vital for multicellular life—oxygen. And while we are taught that oxygen is exhaled primarily by trees, in fact, only 28 percent of the gas is exhaled from rainforests. The vast majority of oxygen is created in the ocean, by phytoplankton and algae. The source of this photosynthesis is one and the same, however, as both land plants and algae have something in common: they were once hijacked by bacteria.

More than two billion years ago, cyanobacteria evolved an extraordinary superpower: the ability to turn sunlight into food. Using the energy from our nearest star, they began converting water and carbon dioxide into sugars, splitting the remaining oxygen off as by-product. Over time, some species of these cyanobacteria remained aquatic and stayed free-living and independent in the ocean,[13] while others were absorbed by algae and became permanent residents housed inside their organelles, known as chloroplasts.[14] As algal species evolved and migrated onto land, they became the ancestors of modern trees and plants. Which means that these tiny and very ancient engineers sit at the controls of all photosynthesizing plants. And it is they who are responsible for *all* of the oxygen we breathe.

At our feet lies another wildly overlooked ecosystem. Soil is home to a third of all life on the planet, and it is buzzing with

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13 Today, one particular species does this brilliantly. Described as "the most important microbe you've never heard of," *Prochlorococcas* is responsible for manufacturing a full 20 percent of the oxygen we breathe.

14 Like mitochondria, chloroplasts have their own DNA that comes from the cyanobacteria.

biodiversity. Just a single teaspoon of garden soil contains a population of about a billion bacteria. In terms of biomass, that's the equivalent of about two cows per acre. One handful of forest soil contains more microbes than there are people on Earth, and one kilogram of healthy soil contains more microbes than all the stars in our galaxy. Van Leeuwenhoek could never have dreamed how vast the universe under the microscope would prove to be. But even today, more than three centuries after Van Leeuwenhoek's first discovery, much of this subterranean cosmos of bacteria, archaea, fungi, protozoa, algae, and viruses remains unexplored. So far, only 0.001 percent of microbial species are known to science.

Soil, of course, is critical for food. Without good soil we'd starve. And today, we understand one of the key roles certain bacteria play with respect to plant growth. That's because plants, like all living beings, need nitrogen for their DNA. In the soil, these bacteria have the ability to take atmospheric nitrogen, which is a gas, and "fix" it so that it turns into a form, like ammonia, that plants can use. In essence, nitrogen-fixing bacteria are like tiny "soluble bags of fertilizer" in the soil, feeding the plants their chemical nutrition and in turn enriching every animal on the food chain.

Beyond their habitats on land and in the oceans, bacteria have also been found swirling high up in the atmosphere. Travelling with NASA's hurricane researchers, scientists sampled a cubic metre of air at 33,000 feet and netted over 5,100 species. Our planet is surrounded by a literal bubble of bacteria. Right now, we are only just beginning to find out what these tiny beings are doing up there. Some scientists believe they play an active role in creating clouds and seeding rainfall, while others say they may be recycling nutrients high up in the atmosphere. There is one thing at least we know for certain: far from being insignificant, the smallest life forms on Earth play a critical role in engineering the planet's life-support

systems. We have long been blind to the invisible services that bacteria provide, but in truth, we owe them our lives.

OUR FIRST BLIND SPOT is that reality is not human-sized. What we call reality is only a tiny sliver in the grand scheme of things. And while we seldom think about size, size is arguably the most important attribute of an animal's existence: it shapes where, how, and even for how long[15] we live on this planet. When it comes to life on Earth however, size does have its limits.

The parasitic wasp called a fairyfly, for instance, is just two hundred microns across. That's about the size of an amoeba, meaning a family of five of these tiny wasps could fit comfortably on the period at the end of this sentence. But what's incredible about the fairyfly is that, unlike an amoeba, it is not a single-celled organism. It's a complex multicellular life form that has managed to squeeze an incredible amount of biological material into an unbelievably minute package. Inside their bodies, these animals have the basic biological architecture of a beating heart, wings, legs, a digestive system, and a functioning brain. So how does it all fit? For the fairyfly, being small comes at a hefty price, and they pay it in brain cells.

Scientists have discovered that by the time they're adults, fairyflies have sacrificed the nuclei in 95 percent of their neurons, which is where the genetic material is stored in the cell. What that means is, for insects, going even smaller becomes next to impossible. For brainless bacteria, there is still space to shrink. While only five fairyflies could fit on a period at the end of a sentence, hundreds of thousands of single-celled bacteria could occupy the same space. When it comes to size, then, bacteria guard this final frontier. Multicellular life cannot get smaller because there's not enough

15 Small animals tend to live shorter lives.

room for its essential ingredients: proteins and DNA. Meaning life, quite literally, cannot squeeze itself in.

On the opposite end of the spectrum there are the giants: the multicellular animals that operate at our size and the few that are even bigger. So, what then are the limits of large living things? Why are there no real-life King Kongs,[16] Godzillas, or fifty-foot women? The first person to tackle that question was, fittingly, a kind of Goliath himself: the famed stargazer and scientific revolutionary Galileo Galilei.

What Galileo realized was that size not only matters, it can be a matter of life or death. In *Discourses and Mathematical Demonstrations Relating to Two New Sciences*, he wrote, "Who does not know that a horse falling from a height of three or four cubits will break his bones, while a dog falling from the same height or a cat from a height of eight or ten cubits will suffer no injury? Equally harmless would be the fall of a grasshopper from a tower or the fall of an ant from the distance of the moon." In essence: Why would a big animal fall to its death while a small animal could walk away without injury?

Galileo's brilliance was in realizing that if you continued scaling an animal up, at a certain point it would begin to break under its own weight. Just as a tree would no longer be able to support the heft of its massive branches, a fifty-foot giant could not take a step without cracking the bones in her limbs.[17] For the behemoths on Earth, then, it's the laws of physics, and gravity in particular, that puts a limit on things.

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16 The largest recorded ape primate in the fossil record was *Gigantopithecus blacki*, a three-metre- tall ape. It was doomed by its size in a different manner, however. During the Ice Age, the food supply became insufficient to support the giant ape.

17 For more on size I direct the reader to J.B.S. Haldane's paper "On Being the Right Size."

The observant among you however, must be thinking, what about dinosaurs, or whales? The biggest sauropods were as tall as a five-storey building, and even blue whales measure about the same as three school buses parked end to end. So how come they are so big? It turns out, these massive animals evolved some impressive workarounds.

Dinosaurs got around the heavy bone problem by becoming pneumatic. The titanic reptiles, like their bird descendants today, had light, hollow bones with large air pockets inside them. In fact, 10 percent of *T. rex*'s body volume was air, and in studying sauropod skeletons, scientists have discovered that their bones were up to 90 percent air by volume. Whales solved the problem by evolving in water. Like all living things, a whale's cells contain saline. In the simplest terms, being primarily *made of salty water* and swimming in salty water allows these leviathans to grow to massive sizes and weigh up to 144 metric tons, because, living in the ocean, they're essentially weightless.[18]

There is, however, another invisible medium that can affect an animal's size, and, like water for whales, it's something we barely notice: the air. That vaporous cocktail we all breathe has changed significantly over the ages. And, along with it, so has the size of life.

If you could hop in a time machine and turn the dial back to between one hundred and four hundred million years ago, like Alice, you would emerge into a gargantuan Wonderland. Because this was the age of giants. In this ancient world, mushrooms rose to the height of houses, hawk-sized dragonflies swooped through

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18 Another factor that scientists believe may affect how marine animals grow to be big in water has to do with loss of heat. Marine mammals grow bigger and have more blubber, as they increase their volume to surface area. This allows them to generate more heat but lose less of it through the surface area of their skin.

the skies, and even dinosaur fleas were ten times larger than their modern counterparts.

Invertebrates were free to grow because for them the weight of bones was not an issue. But there was something else that limited their growth. Kirkpatrick Sale, the author of *Human Scale*, describes the problem like this: "If an earthworm were ten times bigger, its weight would be a thousand times greater, and its need for air a thousand times greater, but the surface area through which it absorbs oxygen would only be a hundred times greater, so it would get only a tenth of the air it needed and would immediately die." So how did prehistoric worms grow in size and still manage to survive? The answer was the concentration of oxygen. In our atmosphere today, oxygen makes up 21 percent of the air, but during the Carboniferous era[19] its concentration was much higher, at 35 percent. For animals like worms that breathe not through their mouths but through pores in their skin, each breath packed a more powerful punch and delivered enough oxygen for them to survive.[20]

We can count ourselves lucky today that there aren't dog-sized cockroaches scuttling through our kitchens. That's because insect gigantism came to an end when another animal rose to prominence. One hundred and fifty million years ago, dinosaurs evolved into a new kind of flying predator: birds. For insects trying to make a quick getaway, the slight and streamlined among them fared better than the big and bulky. Evolution

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19 The Carboniferous era was specifically from the Devonian period 358.9 million years ago, to the beginning of the Permian period, 298.9 million years ago.

20 Having a larger volume to surface area also meant that the oxygen amount would still be relative to body size, so the animals wouldn't die from oxygen toxicity either.

favoured a smaller body size for escape, and insects began to shrink.[21]

The size of a species is not accidental. It's a fine-tuned interaction—a back and forth—between a species and the world it inhabits. Over large periods of time, size fluctuations, from dwarfism to gigantism, have often signalled significant changes in the environment. Generally speaking, however, over the last five hundred million years, the trend has been towards animals getting larger. It's particularly notable in marine animals, whose mean body size has increased 150-fold in this time.[22]

But we are beginning to see big changes again. Scientists have discovered that many animals are shrinking.[23] Around the world, species in every category—fish, bird, amphibian, reptile, and mammal—have been found to be getting smaller, and one key culprit appears to be the heat.[24] Animals living in the Italian

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21 There are many interesting incidences of size changes due to environment. Of note, there is Foster's rule, which states that in island environments large animals tend to develop smaller bodies due to restricted food sources, and small animals tend to get larger due to limits in predation. An example of this can be found in mammoths. A mammoth species that lived in Crete, 3.5 million years ago, stood about only one metre at the shoulder.

22 Looking at more than 17, 000 marine species, researchers have found that since the time the animals first evolved, body volumes have increased by five orders of magnitude.

23 As always, there are exceptions. For instance, climate change is making wolf spiders bigger.

24 Historically, scientists have documented mammalian dwarfing during warming periods in the Earth's history. And during the Palaeocene-Eocene Thermal Maximum, a warming phase of three degrees that took place fifty-five million years ago, some mammals shrank by up to a third, while insects like beetles, ants, and bees shrank by three-quarters.

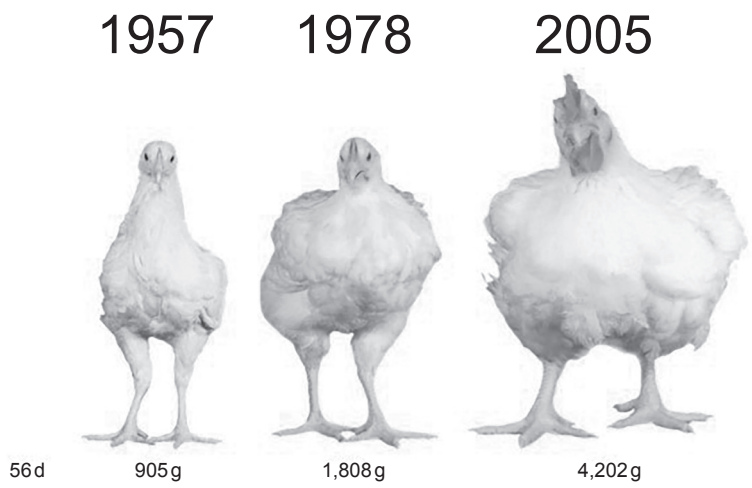
Alps, for example, have seen temperatures rise by three to four degrees Celsius since the 1980s. There, even at an altitude of one thousand metres, heat waves have spiked the alpine temperatures to as high as 30°C. To avoid overheating, chamois goats now spend more of their days resting rather than foraging, and as a result, in just a few decades, the new generations of chamois are 25 percent smaller, and are dwarfs by comparison. Underwater too, sea temperatures have begun to rise, one consequence of which is that the water holds less oxygen and becomes more anoxic. Scientists studying six hundred species of fish say that big size changes are coming and that by 2050 fish will have shrunk by as much as a quarter.

Shrinking potentially signals an even bigger problem: a population crash. Looking at commercial whaling data over four decades, researchers documented that sperm whales shrank substantially—by four to five metres—in the years before their populations collapsed. For biologists, then, shrinking is like an early warning system, alerting us that a species may be in trouble.

But not all animals are shrinking. Domestic species that we raise for food, like pigs and cows, for instance, are growing faster and larger than at any time in history. Since the 1930s, turkeys have more than doubled in size, and since the 1950s, broiler chickens have quadrupled.

To track the changes, Canadian researchers have continued raising unmodified chicken lineages and have measured them against our modern Frankensteins. Like living, breathing, chicken time capsules, these "benchmark strains" are still being bred. This allows researchers to measure commercially selected breeds, like the 2005 Ross 308 Broiler, against older genetic strains. Fed the same food, and measured at the same age, the 1957 strain weighed in at 905 grams, the 1978 strain weighed 1,808 grams, while the 2005 strain weighed 4,202 grams. The difference is enormous. Compared to birds from the 1950s, today's modern broilers have

breasts that are 80 percent larger and have increased overall in size by 400 percent.



There is a consequence to this. As we've deliberately grown larger animals for food, our appetites have grown as well. In 1960, the average American ate 12.7 kilograms of chicken a year, today that number has jumped to 40.8 kilograms, more than three times as much.[25] Unsurprisingly, as the beneficiaries of all this cheap meat, humans have also begun to change in size. Over the last 150 years, which is, relatively speaking, a short period, human height has increased dramatically. In industrialized countries, where is food abundant, we've grown taller by ten centimetres. Not only have we expanded upward though, we've expanded outward as well, and every country on Earth

25 The average consumption of both red meat and poultry in 1960 was 75.3 kilograms, in 2017 it was projected at 98.8.

has seen its obesity rates rise.[26] In total, 2.2 billion people worldwide are classified as overweight or obese, and adults are three times more likely to be obese than they were back in 1975. Today, wild animals world over are shrinking, but human beings and our domesticated animals are ballooning in size.

GALILEO WAS THE FIRST person on Earth to glimpse the colossal scale of reality.[27] Known today as the Father of Science, he was not only the first person to burst open the heavens with a telescope, he was also the first man to peer into a microscope and document the humble flea. It was Galileo's good fortune to be alive at a time when glass-making was flourishing, in particular the craft of making spectacles. Then, as now, people in their forties often developed presbyopia, a condition where the lens of the eye loses flexibility with age, making it more difficult to read. In nearby Holland, the Dutch had become masters at grinding lenses to make reading glasses, and it was these spectacle makers who crafted the first rudimentary instruments that allowed us to bring into focus scales that were previously unseen.

Their intent may have been to remedy poor vision, but the spectacle makers inadvertently did much more. By boosting our vision, they revealed that humanity had been oblivious to two vast scales that secretly co-existed alongside our own. The macro and micro worlds were now made visible, and with this new and improved sight came the realization that we inhabit not only one reality, but three.

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26 Twenty percent of Pacific Islanders living into Tonga and Tuvalu are classified as obese, and even North Korea has seen a gain of 1 percent.

27 The first published observations using a microscope were in Galileo's *Apiarium* in 1625. He first observed the flea with a microscope in 1624.