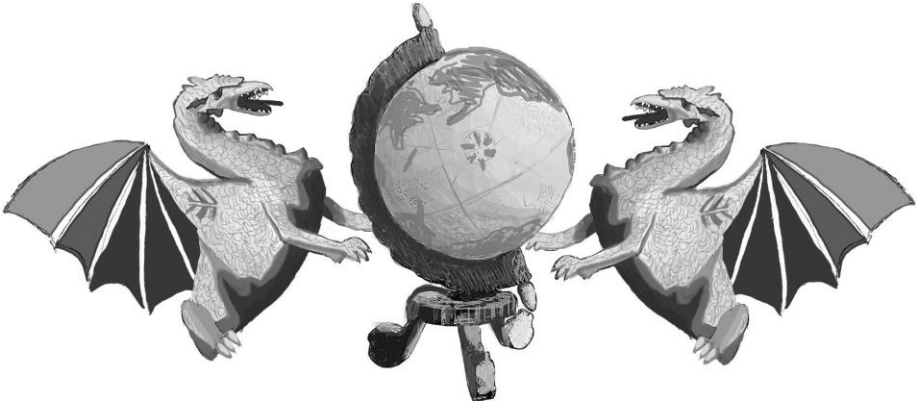
THE DRAGONS ARE BACK 1



JUST below the equator, off the eastern coast of Asia, a long-forgotten mapmaker etched the warning "HC SVNT DRACONES" on a tiny copper globe. Sketches of sea monsters, twisted serpents, and wild beasties adorn the globe, as they do in many medieval maps. The strange creatures signaled uncharted territory to seafaring explorers. Unknown lands, danger, darkness, or perhaps riches lay beyond.

The copper globe, a rare treasure inscribed with the Latin words meaning "here be dragons," resides in the New York Public Library's collection of ancient treasures. It reminds us that there was a time, not so long ago, when uncertainty prowled just beyond the waves. Today, maps chart in fine detail the contours of hills, mountain ranges, the ocean floor, coastlines, and cities. Mapmakers can trace every last reach of the planet with great precision.

But the sophisticated surety of modern maps is deceptive. Dragons still lurk but in a different guise. No one can predict the surprises in store for our hyperconnected, complex civilization, just as medieval explorers could not foresee what lands lay beyond the beasts. Despite vast knowledge about the world, much remains unknown. Precisely when and where a stock market might crash, a political upheaval might upend the norm, a spark might ignite a wildfire, a drought parch the soil, or a deadly disease spread through an unprepared population are impossible to predict. All these disasters lurk in the shadows of the unknown. We live in an age of uncertainty. With a restless planet pushed off-balance from the by-products of an energy-guzzling civilization, and a fragile network that connects nearly everyone on the planet, dragons are all around us.

Modern civilization is ill-equipped and unprepared to navigate through these dragon-filled times. Until the havoc from the coronavirus pandemic hit every aspect of daily life, few paid attention to the warnings from little-known scientists. They cautioned that humanity needs to be on the watch for dangerous viruses that inevitably make the jump from wildlife to human. Other examples of our vulnerability are so common that we hardly recognize them. Engineers design buildings to withstand wind gusts and storm surges experienced within recent memory rather than future possibilities. People purchase homes assuming that forest fires will not threaten their communities, unaware that the future might bring flames to their doorsteps. Ice caps that locked up water for all of human civilization could crash into the sea, flooding coastlines and cities that are home to millions and economic engines for jobs and trade. People in places that become too hot or too dry to eke out food and livelihoods will have little choice but to move their families to more hospitable climes, with little prospect that people in those places will welcome them with open arms.

The human species has no experience living in a world with an atmosphere that has not existed for the last three million years. Even the most sophisticated science and advanced models cannot make up for a basic reality. How our exquisite and ever-changing planet—along with the bounty of life that it harbors—responds to an unprecedented atmosphere is too complex for the human mind to comprehend. Surprises are in store. Unexpected repercussions for diseases, pests, and the plants and animals that provide us with food, water, and clean air are sure to test civilization's capacity to cope.

Another dragon lurks beside the uncertainty about the planet's future from the heat-trapping by-product of energy sucked from long-buried dead plants and animals. People across the world depend on distant places for survival like never before. The story of modern civilization rests on copious energy unleashed from coal mines and oil rigs that replaced the labor of people and animals. With abundant energy, a small handful of people can grow enough food to support many people crowded together in cities. Ships, trucks, and planes can move goods around the world.

Our species has meager experience surviving in our interconnected, urban world. For the vast majority of human existence, people lived scattered around the world, barely aware of one another's existence. Today, billions of people in modern economies rely on a web of dependencies for food, medicines, and other goods essential for survival. A kink in the vast web of trade networks can ricochet and cascade in directions that are not possible to foresee, as we'll see in a later chapter.

The twin dragons of a changing climate and an interconnected economy shape the future. Twentieth-century hubris that our collective knowledge is sufficient to predict and plan is falling by the wayside. Twenty-first-century civilization will persist through nimbleness and resilience founded on the reality of an inherently unpredictable future.

As the recent past no longer serves as a guide for the future, nature's long experience sheds some light. Life in one form or another, whether tiny cells, scaly reptiles, or fur-covered mammals, has flourished for billions of years through catastrophic swings in climate, asteroids crashing into Earth, and mass extinctions. Over deep time and through trial and error, and without intent or preplanned design, surprising tricks to stay nimble and resilient evolved in nature.

Planners, engineers, investors, and governments are unwittingly rediscovering these strategies, from the design of the internet to international negotiations. They are learning that the twentieth century, silver bullet–driven paradigm of efficiency and technological progress cannot protect us from unpredictable fires, storms, market crashes, diseases, and the uncertainty that permeates our complex world.

This book tells stories of these counterintuitive and underappreciated strategies, honed by evolution over billions of years. Collectively they offer a fundamentally different mindset for humanity to persist in the complex, interconnected, and uncertain world of the twenty-first century.

ROME TO TRANTOR

Isaac Asimov, the most prolific science fiction writer of all times, saw it coming. Any complex civilization that becomes too rigid will eventually crumble from encounters with dragons in the form of invasions, political crises, storms, or droughts, among many types of unknowable insults. That's what happened to Asimov's Galactic Empire in his fantastical history of the future some twenty thousand years hence.

Emperor Cleon I presides over the vast galaxy from Trantor, the fictional planet that Asimov introduced to his fans in the first of many novels, *Pebble in the Sky*. Trantor, located at the center of the galaxy, is home to 45 billion people who perform administrative tasks to serve the empire. They live in a giant, dome-covered metropolis that covers the entire planet with highways, living spaces, and human-made structures. Trantorians never see the sky; they are afraid to go outside the dome. Their nutrients come from underground yeast vats and algae farms. The rest of the food comes by spaceship from outer-world planets. The same ships carry away the Trantorians' waste.

Asimov's imagination traveled far into the cosmos, but on Earth he was an imperfect character. He notoriously groped women at every opportunity, grabbed their behinds without their consent, and snapped their bra straps. He liked to work on his copious writings in small, windowless rooms; he rarely left his New York apartment; and he abhorred travel. He might have felt at home on Trantor. He was also a biochemist, so he knew that a civilization depends most fundamentally on its sources for food and its prospects for disposing of wastes.

The Galactic Empire's central-control strategy does not end well in Asimov's vision. The empire collapses from overreliance on the outer planets and the sheer complexity of ruling the vast galaxy. Asimov took his inspiration from the downfall of the Roman Empire to conjecture a fictional future.

The year ad 476 marked the official end of the Western Roman Empire. Romulus Augustulus, the last of many emperors, surrendered the crown to the Germanic rebel Odoacer. The complex society that had persisted for over a thousand years, with a sophisticated economy, military, and transport system, broke down with no central authority. People fled crumbling cities across the empire, from Roma to Londinium, and retreated to the countryside.

The Roman Empire and other complex societies throughout history functioned through vast networks of connections and dependencies among distant peoples and places. The empire at its height spanned from North Africa to Britain and from Armenia to the Atlantic Ocean. Even common citizens enjoyed material comforts enabled by trade with faraway places. Peasants in central Italy ate from finely crafted pottery manufactured in North Africa and stored their wines and oils in high-quality jars. Graffiti scribbled on buildings and brothel walls hints that many common people could read and write.

Such a sophisticated economy required a high degree of specialized tasks. Some people were skilled potters; others were scribes, professional soldiers, engineers, poets, tax collectors, butchers, bakers, farmers, teachers, and prostitutes, while slaves carried out menial tasks. Some sweated over clay furnaces to make coins from mined silver. The economy was so far-reaching that its ups and downs with wars, plagues, and conquests are to this day recorded in Greenland ice cores. Lead, swept into the air from the furnaces, rained down and froze in layer upon layer of ice.

Trade networks contracted as the complex society dissolved, and material comforts went by the wayside. Tiled roofs and stone floors, common in peasants' houses during the Roman Empire, became a rare luxury. A few decades after the downfall, most people lived in tiny houses with dirt floors and insect-infested thatched roofs. Fine pottery was gone from the kitchens. People no longer scribbled graffiti as literacy became less common.

Historians and archeologists have puzzled for centuries over the causes of the decline of such a sophisticated society. The story sparks fascination because it hits close to home: highly interconnected economy, large cities as hubs, and many specialized tasks; material comforts that far surpassed prior times; strong state controlled military supported from tax revenues; sophisticated technologies; extensive roads and ports to move goods, people, and armies; and a long-lived civilization that people thought would continue forever. The proximate reason for the downfall rests on Germanic and Hun invaders who infiltrated the empire, sacked Rome, and snatched power from the emperor. But the Roman army had resisted similar attacks two centuries earlier. It could no longer muster the strength. Other reasons made the civilization ripe for decline.

A German historian catalogued from A to Z no less than 210 ways that his colleagues have explained these underlying reasons. Under *C* is Christianity, which burdened society with nonproductive monks and ascetics whose only contributions were abstinence and celibacy, and Corruption as imperial authorities sold favors and military officials extorted money from civilians. Under *P* is Plagues, with waves of bubonic plague that killed so many people that dead bodies clogged city streets. The list goes on: Earthquakes, Excessive Urbanization, Hubris, Soil Exhaustion, Taxation, and Two-Front War. Historian Bryan Ward-Perkins sums up the situation: "Because the ancient economy was in fact a complicated and intertwined system, its very sophistication rendered it fragile and less adaptable to change."

Asimov could have chosen any of history's complex societies for his science fiction view of the distant future. Each has its own mystery shrouded under vines in thick jungles overgrowing ancient carvings, desert sand blown over remnants of abandoned cities, or mountaintops adorned with elaborate temples. Each complex society has its own art, architecture, cuisine, culture, and unique story of its pathway to decline. But they all share common elements, from the sophisticated, urbanized Indus Valley civilization that thrived many millennia ago to the Anasazi who abandoned their iconic cliff dwellings in the American Southwest as recently as the thirteenth century. They all had stratified societies, bureaucracies, and cities supplied with surplus food from the hinterlands. All depended on trade and connections to make society function. Dependencies made them efficient, but those dependencies also made them vulnerable. They were all complex, as measured by the numbers of specialized jobs, trade routes, or reliance on others for the necessities of everyday life.

Political power grabs, enemy invasions, plagues, or a drought or flood could trigger cascading shocks throughout the connected, complex systems. Any one of these triggers could bring down networks that distributed food and essentials to people in the cities or cut off an authority's supply of tax revenue. In the case of the lowland Mayan, for example, the trigger might have been drought that accelerated the long, slow decline set in motion by a rigid, urban ruling elite who resisted change. Steady decline allowed the trigger to spark a collapse.

As in ancient Rome, complex societies brought great benefits, as people could engage in culture-building tasks rather than procure their own food. Each family or small group of people did not have to separately learn how to grow grain, store and mill it, and bake bread. The complex system was efficient. But eventually the complexity made the systems brittle. They became locked into rigid, inflexible institutions and traditions. Bureaucracies and entrenched rulers outgrew the ability to adjust when potential triggers to their downfall inevitably occurred. Or perhaps the rulers became intoxicated with power and wouldn't let go even if it meant their own demise.

Today's world is not similar to Trantor. People still go outside. They see the sky. They eat food grown in Earth's soil. Cities do not engulf the entire planet; rather, they occupy only a small portion of land. Nor is today's world completely analogous to the Roman Empire or other historical complex societies. Today there is no central command from an emperor. Science and technology have extracted copious energy from nonhuman and nonliving sources so that only a few need to engage in producing food in industrialized societies. Knowledge to control the spread of plagues far surpasses the past. But today's world is highly complex and interdependent, more so than any time in the past. Most people in the world live in cities, perform specialized tasks, and rely on trade networks for nearly every aspect of their material existence. The efficiency is high and the benefits are enormous. But the vulnerability is great. In the words of WardPerkins summarizing the learnings from the fall of Rome, "The main lesson . . . is not some specific panacea that can preserve our civilization forever . . . , but a realization of how insecure, and probably transient, our own achievements are—and, from this, a degree of humility."

We might look with humility to life's success over billions of years on our planet for clues to navigate the dragon-ridden seas of the current day.

FROM CLOCKWORK TO COMPLEXITY

The common ancestor to all life emerged in a primordial soup of chemicals. At that moment, predictable chemistry and physics of the early Earth gave way to unpredictable complexity. A primitive cell, the master foreparent of all whales, grass, humans, trees, fish, bacteria, elephants, microbes—all life on Earth—lived sometime in the first billion years of the planet's 4.5-billion-year history. It thrived in the deep sea where underwater volcanoes vent heat and spew a cocktail of chemicals into seawater.

Once life was under way, the planet and its biosphere were not just complex. The interacting oceans, atmosphere, and life became, in the nomenclature of scientists who study such phenomena, a complex adaptive system. When parts of the system are connected and each is able to adjust to its surroundings, as ancient cells can do, feedbacks cascade and reverberate through the system. The system constantly adjusts and changes unpredictably.

Kevin Kelly, the eclectic writer and astute observer of technology, nature, and organizations, posed a riddle to experts in adaptive systems: What color is a chameleon on a mirror? The camouflaging lizards, with their distinctive ability to change color to blend with their surroundings, might not enjoy the experiment. But the speculations from the experts are revealing. A range of unexpected outcomes ensue from the back-and-

forth exchange as the chameleon tries to blend with the color that the chameleon itself is reflecting into the mirror.

One expert asserts that the creature would settle at the middle value in its color range. Kelly himself thought that "the poor beast trying to disappear in a universe of itself would endlessly cycle through a number of its disguises." Another opined that the colors would fluctuate chaotically in a random, psychedelic paisley. Yet another idea was that both the chameleon and the mirror would freeze into the chameleon's initial color. The possibilities are endless and would likely be different for each chameleon–mirror pair. The chameleon might turn red, which it tends to do when scared, setting off a scarier and scarier escalation as the mirror reflects back a frightened chameleon. Or, because the chameleon and mirror cannot be truly isolated, the image of the observer might get reflected in the mirror and set off another color change in the chameleon if someone is watching to see what happens. Uncertainty rules in a complex adaptive system.

The riddle is fun to think about, though a bit cruel to the chameleon. On a much grander scale than a chameleon perched on a mirror, exchanges between life, the atmosphere, the ocean, and back to life again is the never-ending story of Earth's extremely complex, adaptive, and self-correcting system throughout its long history.

Bacteria's early switch in survival strategy set off cascading feedbacks that changed the course of all life to come. For a billion years, simple bacteria dominated life with their strategy to extract hydrogen from hydrogen sulfide and combine it with carbon and energy from the sun or from deep-sea vents to produce sugars. Then bacteria expanded their repertoire to extract the necessary hydrogen, not from hydrogen sulfide in swamps or in the sea but from ubiquitous hydrogen bonded with oxygen, in other words, water. That seemingly small adjustment cascaded into blue-green algae that revolutionized life.

Oxygen was a by-product of the water strategy for extracting hydrogen. At the time, life was adjusted to the low-oxygen atmosphere. As oxygen, the blue-green algae's waste product, built up in the atmosphere around two and half billion years ago, the feedback was fatal for some. Bacteria accustomed to low-oxygen conditions retreated to airless, stagnant waters. They were locked into their low-oxygen strategy and couldn't adjust. But the rising oxygen that led to their downfall was a boon for other life.

Green photosynthesizing plants thrived from bacteria's disaster as enough oxygen built up in the atmosphere to shield them from harmful ultraviolet radiation from the sun. Flowerless liverworts, so named for their small, liver-shaped waxy lobes, and hornworts with green, spiky tubes, then mosses, ferns, and cone-bearing plants dominated life on land for millions of years. Then sponges, corals, and jellyfish flourished in the oceans, followed by insects, reptiles, dinosaurs, mammals, and other animals on land.

With animals on the scene, plants had more options beyond wind and water to disperse their seeds. Flowering plants could co-opt bees, birds, and butterflies for procreation with the allure of nectar. Wings and feet of mobile insects and birds could deliver male pollen from inside a flower to the female ovule. The brokered match fertilized the plant's seeds, a task that a stationary plant could not achieve on its own. Plants developed vivid colors and shapes to attract pollinators. Pollen that rubbed off on a hummingbird's head when it dipped its long slender bill into a brightly colored flower for a sip of nectar, for example, traveled along when the hummingbird moved on to the next flower. A similar strategy emerged in fruit-bearing shrubs and trees to entice birds, and later rodents, bats, lizards, and any fruit-loving animal, with the juicy flesh of the fruits. Animals eat the seeds along with the fruit's flesh and scatter seeds where they defecate.
The new strategies brought another level of dependency and complexity to life.

Life had to contend not only with the problems it created for itself but with erupting volcanoes and bombardments from space. About 250 million years ago, ashes and gases from colossal volcanoes blocked out sunlight and obliterated most forms of life including trilobites, corals, and other marine creatures. But life was far from defeated and roared back in different forms. Another possible life-busting would-be disaster

occurred about 66 million years ago. A massive collision between a comet and the Earth spewed dust into the atmosphere and again blocked the sun's energy. Many life forms didn't survive the calamity, including the dinosaurs. The dinosaur's disaster made way for mammals to dominate.

One species of those mammals, *Homo sapiens*, became a dominant planetary force only a short time ago in evolutionary terms. For most of our species' 300,000-year history, people foraged for edible fruits and seeds and hunted animals for meat. They existed within the planet's complex system, which provided a diversity of plants and animals, stable climate, and resilience that served life well for billions of years.

About twelve thousand years ago, the survival strategy shifted from hunters and gatherers to settled farmers. Surplus cereals underpinned hierarchical societies, as an elite class could control the food stocks. Settlements of groups of people, trade of foods and ideas, communication, labor-saving technologies, and economies with specialized tasks cascaded into human-created complex societies.

An industrial economy, powered by long-buried plants and animals in the form of coal, begat another leap in the complexity of civilization as recently as a few centuries ago. People left the countryside and moved to cities to work in factories, open shops, and provide services to keep the economy humming. Most people are now urban dwellers in our interconnected, modern world. Like the Trantorians in Isaac Asimov's Galactic Empire, an urban dweller depends fundamentally on connections and dependencies for survival. In the hours that an urban dweller works in an office, factory, or business, or lounges on a couch, someone else is growing the food, pumping the water, generating the energy, bringing the food and water and energy to the city, and taking away the wastes. In turn, urban dwellers work at a myriad of jobs that connect with other people and make society function.

An urban dweller lives a life of invisible connections unprecedented in civilization. Of course, this picture is vastly oversimplified. The complexity of all the interactions needed to keep a city-world fed and housed with sufficient water and energy, and without wastes piling up, boggles the mind. The networked, interconnected system is so complex we can hardly comprehend it, much less control it. Our modern, global civilization and its flows of information and goods resemble more a living, breathing superorganism than a predictable, controllable machine.

A machinelike, clockwork view of the world, promoted by the French father of Western philosophy René Descartes and English physicist and theologian Isaac Newton, guided science and rational thought through the seventeenth-century Enlightenment. Descartes and Newton implanted the notion that the sum is equal to the parts. Knowledge and control are gained from breaking each system—the cosmos, the human body, the economy, or an aircraft—into its individual pieces.

In a simple machine, outcomes are predictable. A gear turns a lever that turns another gear. Every time someone flips a switch, the gears and levers turn the same way with the same response. Even a complicated machine with many parts is predictable and reliable. Push the accelerator of a car and the speed will go up by a predictable amount. Not so when complexity enters into the picture. One part of the system affects another that affects another, while the first part adjusts and sets off another reaction. Uncertainty reigns. No predictable levers can guarantee a reliable and repeatable outcome. It's a chess game, except no one can pretend to know all the rules or the opponent's next move.

Laws of mechanics act like clockwork. Laws of life lead to complexity. When complexity is at play, when the sum is greater—or lesser—than the parts, the clockwork view can lead to hubris. In a living system that is constantly adjusting to its surroundings, a change in one cell, organ, species, or ecosystem can set off a chain reaction that propagates across all the connected parts. Life is always vulnerable to unforeseeable outcomes. The same is true for ancient Rome, the fictional Galactic Empire, and modern civilization. A political uprising, a cutoff in supplies from a distant source, or an unfamiliar dry spell or storm can overwhelm a rigid bureaucracy and cascade through society.

Life on Earth withstands such unforeseeable shocks with a few simple strategies. This book is about some of these strategies and the clues they hold for modern civilization to navigate through uncertain times. You will see that people, businesses, governments, and societies are beginning to retool the way they plan, invest, and make decisions based on the twenty-first-century fundamental reality of an unpredictable future. Their new ways of planning and doing business run counter to the twentieth- century, clockwork view that places efficiency above all else and plans around a predictable future. Unwittingly and sometimes accidentally, they are learning that nature's strategies are the only way to survive in a world full of dragons.

Through trial and error, ideas brewing from the scientists who devote their careers to unraveling the secrets of nature's complexity are starting to prove their relevance in the real world. If civilization is to thrive and prosper, the stories in this book of the initially unwelcome and ultimately successful design of the internet, fortuitous demise of the deadly smallpox virus, rescue of the midwestern wheat crop by a faraway wild grass, and hard-fought cooperation among countries to clean up the atmosphere, among others, are only the beginning of new tools in the tool kit for civilization to thrive and prosper through a dragon-filled future.

In short, and following the order of subsequent chapters, some of nature's strategies that are proving their worth for our human constructed societies: built-in *self-correcting features*, a stabilizing strategy pervasive in nature and adopted by the stock exchange to catch a free-falling plunge in the market; *diversity*, the hallmark of both financial investors and the natural world, to buffer against an unknown future, keep options open, and safeguard valuable knowledge and ideas from coalescing into a globally homogenous stew of culture, cuisine, and ways of viewing the world; the architecture of ubiquitous *networks*, patterned on tiny veins in a leaf, to keep the flow of goods, food, information, and ideas safe from cascading failure and, conversely, to prevent lethal diseases from spreading; and leaders who enable decisions based on *bottom-up* knowledge of local conditions, the way ants and termites build their fabulous structures, rather than top-down impositions from faraway authorities that inevitably backfire. These are nature's time-tested tactics that maintain life through unknown futures and cycles of renewal. As the clockwork world of the twentieth century recedes into the rearview mirror, these strategies hold the keys to our prosperity and persistence in our dynamic, interconnected, complex world.