WORK

A DEEP HISTORY, FROM THE STONE AGE TO THE AGE OF ROBOTS

JAMES SUZMAN

ALSO BY JAMES SUZMAN

Affluence Without Abundance

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Why should I let the toad *work*
Squat on my life?
Can’t I use my wit as a pitchfork
And drive the brute off?

Philip Larkin, “Toads”

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INTRODUCTION

THE ECONOMIC PROBLEM

The first industrial revolution was coughed out of the soot-blackened chimneys of coal-fired steam engines; the second leaped from electric wall sockets; and the third took the form of the electronic microprocessor. Now we are in the midst of a fourth industrial revolution, born of the union of a host of new digital, biological, and physical technologies, and we are told that it will be exponentially more transformative than its predecessors. Even so, no one is yet quite sure how it will play out, beyond the fact that ever more tasks in our factories, businesses, and homes will be undertaken by automated cyber-physical systems animated by machine-learning algorithms.

For some, the prospect of an automated future heralds an era of robotic convenience. For others, it is another fateful step on the journey toward a cybernetic dystopia. But for many, the prospect of an automated future raises only one immediate question: what will happen if a robot takes my job?

For those in professions that have up to now been immune from technological redundancy, the rise of the job-eating robots manifests in the mundane: the choruses of robotic greetings and reprimands that emanate from the ranks of automated tellers in supermarkets or the clumsy algorithms that both guide and frustrate our adventures in the digital universe.

For the hundreds of millions of unemployed people scraping a living in the corrugated-iron margins of developing countries, where economic growth is driven ever more by the marriage of cutting-edge technology and capital and so generates few new jobs, automation is an altogether more immediate concern. It is also an immediate concern for ranks of semi-skilled workers in industrialized economies whose only option is to strike to save their jobs from automata whose principal virtue is that they never go on strike. And, even if it doesn't feel like it just yet, the writing is on the wall for some in highly skilled professions too. With artificial intelligence now designing better artificial intelligence than people can, it looks like we have been tricked by our own ingenuity into turning our factories, offices, and workplaces into devil's workshops that will leave our hands idle and rob our lives of purpose.

If so, then we are right to worry. After all, we work to live and live to work and are capable of finding meaning, satisfaction, and pride in almost any job: from the rhythmic monotony of mopping floors to gaming tax loopholes. The work we do also defines who we are; determines our future prospects; dictates where and with whom we spend most of our time; mediates our sense of self-worth; molds many of our values; and orients our political loyalties. So much so that we sing the praises of strivers, decry the laziness of shirkers, and the goal of universal employment remains a mantra for politicians of all stripes.

Beneath this lies the conviction that we are genetically hardwired to work and that our species' destiny has been shaped by a unique convergence of purposefulness, intelligence, and industriousness that has enabled us to build societies that are so much more than the sum of their parts.

Our anxieties about an automated future contrast with the optimism of many thinkers and dreamers who, ever since the first stirrings of the Industrial Revolution, believed that automation was the key that would unlock an economic utopia. People like Adam Smith, the founding father of economics, who in 1776 sung the praises of the "very pretty machines" that he believed would in time "facilitate and abridge labor,"[1] or Oscar Wilde who a century later fantasized about a future "in which machinery will be doing all the necessary and unpleasant work."[2] But none made the case as comprehensively as the twentieth century's most influential economist, John Maynard Keynes. He predicted in 1930 that by the early twenty-first century capital growth, improving productivity, and technological advances should have brought us to the foothills of an economic "promised land" in which everybody's basic needs were easily satisfied and where, as a result, nobody worked more than fifteen hours in a week.

We passed the productivity and capital growth thresholds Keynes calculated would need to be met to get there some decades ago. Most of us still work just as hard as our grandparents and great-grandparents did, and our governments remain as fixated on economic growth and employment creation as at any point in our recent history. More than this, with private and state pension funds groaning under the weight of their obligations to increasingly aged populations, many of us are expected to work almost a decade longer than we did half a century ago; and despite unprecedented advances in technology and productivity in some of the world's most advanced economies like Japan and South Korea, hundreds of avoidable deaths every year are now officially accredited to people logging eye-watering levels of overtime.

Humankind, it seems, is not yet ready to claim its collective pension. Understanding why requires recognizing that our relationship with work is far more interesting and involved than most traditional economists would have us believe.

* * *

Keynes believed that reaching his economic promised land would be our species' most singular achievement because we will have done nothing less than solve what he described as "the most pressing problem of the human race . . . from the beginnings of life in its most primitive form."

The "pressing problem" Keynes had in mind was what classical economists refer to as the "economic problem" and sometimes also as the "problem of scarcity." It holds that we are rational creatures cursed with insatiable appetites and that because there are simply not enough resources to satisfy everybody's wants, everything is scarce. The idea that we have infinite wants but that all resources are limited sits at the beating heart of the definition of economics as the study of how people allocate scarce resources to meet their needs and desires. It also anchors our markets, financial, employment, and monetary systems. To economists, then, scarcity is what drives us to work, for it is only by working—by making, producing, and trading scarce resources—that we can ever begin to bridge the gap between our apparently infinite desires and our limited means.

But the problem of scarcity offers a bleak assessment of our species. It insists that evolution has molded us into selfish creatures, cursed to be forever burdened by desires that we can never satisfy. And as much as this assumption about human nature may seem obvious and self-evident to many in the industrialized world, to many others, like the Ju/'hoansi

“Bushmen” of southern Africa’s Kalahari, who still lived as hunter-gatherers through to the late twentieth century, it does not ring true.

I have been documenting their often traumatic encounter with a relentlessly expanding global economy since the early 1990s. It is an often brutal story, set in a frontier between two profoundly different ways of life, each grounded in very different social and economic philosophies based on very different assumptions about the nature of scarcity. For the Ju/’hoansi, the market economy and the assumptions about human nature that underwrite it are as bewildering as they are frustrating. They are not alone in this. Other societies who continued to hunt and gather into the twentieth century, from the Hadzabe of East Africa to the Inuit in the Arctic, have similarly struggled to make sense of and adapt to norms of an economic system predicated on eternal scarcity.

When Keynes first described his economic utopia, the study of hunter-gatherer societies was barely more than a sideshow in the newly emerging discipline of social anthropology. Even if he had wished to know more about hunter-gatherers, he would not have found much to challenge the prevailing view at the time that life in primitive societies was a constant battle against starvation. Nor would he have found anything to persuade him that, despite the occasional setback, the human journey was, above all, a story of progress and that the engine of progress was our urge to work, to produce, to build, and to exchange, spurred by our innate urge to solve the economic problem.

But we now know that hunter-gatherers like the Ju/’hoansi did not live constantly on the edge of starvation. Rather, they were usually well nourished; lived longer than people in most farming societies; rarely worked more than fifteen hours a week; and spent the bulk of their time at rest and leisure. We also know that they could do this because they did not routinely store food, cared little for accumulating wealth or status, and worked almost exclusively to meet only their short-term material needs. Where the economic problem insists that we are all cursed to live in the purgatory between our infinite desires and limited means, hunter-gatherers had few material desires, which could be satisfied with a few hours of effort. Their economic life was organized around the presumption of abundance rather than a preoccupation with scarcity. And this being so, there is good reason to believe that because our ancestors hunted and gathered for well over 95 percent of *Homo sapiens*’ 300,000-year-old history, the assumptions about human nature in the problem of scarcity and our attitudes to work have their roots in farming.

Acknowledging that for most of human history our ancestors were not as preoccupied with scarcity as we are now reminds us that there is far more to work than our efforts to solve the economic problem. This is something we all recognize: we routinely describe all sorts of purposeful activities beyond our jobs as work. We can work, for instance, at our relationships, on our bodies, and even at our leisure.

When economists define work as the time and effort we spend meeting our needs and wants, they dodge two obvious problems. The first is that often the only thing that differentiates work from leisure is context and whether we are being paid to do something or are paying to do it. To an ancient forager, hunting an elk is work, but to many First World hunters it is an exhilarating and often very expensive leisure activity; to a commercial artist, drawing is work, but to millions of amateur artists it is a relaxing pleasure; and to a lobbyist, cultivating relationships with movers and shakers is work, but for most of the rest of us making friends is a joy. The second problem is that beyond the energy we expend to secure our most basic needs—food, water, air, warmth, companionship, and safety—there is very little that is universal about what constitutes a necessity. More than this, necessity often merges so imperceptibly with desire that it can be impossible to separate them. Thus some will insist that a breakfast of a croissant served alongside good coffee is a necessity while for others it is a luxury.

The closest thing to a universal definition of “work”—one that hunter-gatherers, pinstriped derivatives traders, calloused subsistence farmers, and anyone else would agree on—is that it involves purposefully expending energy or effort on a task to achieve a goal or end. Ever since ancient humans first began to divide up the world around them and organize their experiences of it in terms of concepts, words, and ideas, they have almost certainly had some concept of work. Like love, parenthood, music, and mourning, work is one of the few concepts that anthropologists and travelers alike have been able to cling to when cast adrift in alien lands. For where spoken language or bewildering customs are an obstruction, the simple act of helping someone perform a job will often break down barriers far quicker than any clumsy utterances. It expresses goodwill and, like a dance or a song, it creates a communion of purpose and a harmony of experience.

Abandoning the idea that the economic problem is the eternal condition of the human race does more than extend the definition of work beyond how we make a living. It provides us with a new lens through which to view our deep historical relationship with work from the very beginnings of life through to our busy present. It also raises a series of new questions. Why do we now afford work so much more importance than our hunting and gathering ancestors did? Why, in an era of unprecedented abundance, do we remain so preoccupied with scarcity?

Answering these questions requires venturing far beyond the bounds of traditional economics and into the world of physics, evolutionary biology, and zoology. But perhaps most importantly it requires bringing a social anthropological perspective to bear on them. It is only through social anthropological studies of societies who continued to hunt and gather into the twentieth century that we are able to animate the flaked stones, rock art, and broken bones that are the only abundant material clues to how our foraging ancestors lived and worked. It is also only through taking a social anthropological approach that we can begin to make sense of how our experiences of the world are molded by the different kinds of work we do. Taking this broader approach offers us some surprising insights into the ancient roots of what are often considered to be uniquely modern challenges. It reveals, for instance, how our relationships with working machines are resonant of the relationship between early farmers and the cart horses, oxen, and other beasts of burden that aided them in their work, and how our anxieties about automation are remarkably reminiscent of those that kept people in slave-owning societies awake at night, and why.

* * *

When it comes to charting the history of our relationship with work, there are two intersecting pathways that are the most obvious to follow.

The first maps the story of our relationship with energy. At its most fundamental, work is always an energy transaction and the capacity to do certain kinds of work is what distinguishes living organisms from dead, inanimate matter. For only living things actively seek out and capture energy specifically to live, to grow, and to reproduce. The journey down this pathway reveals that we are not the only species who are routinely profligate with energy; or who become listless, depressed, and demoralized when they are deprived of purpose and there is no work to do. This in turn raises a whole series of other questions about the nature of work and our relationship with it. Do, for example, organisms like bacteria, plants, and cart horses also work? If so, in what ways does the work they do differ from the work that humans and the machines that we build do? And what does this tell us about the way we work?

This pathway begins at the moment an energy source first somehow bound together a chaos of different molecules to form living organisms. It is also a path that widens steadily and ever more rapidly as life progressively expanded across the earth's surface and evolved to capture new sources of energy, among them sunlight, oxygen, flesh, fire, and eventually fossil fuels with which to do work.

The second pathway follows the human evolutionary and cultural journey. Its early physical milestones take the form of rough stone tools, ancient hearths, and broken beads. Later milestones take the form of powerful engines, giant cities, stock exchanges, industrial-scale farms, nation states, and vast networks of energy-hungry machines. But this is a pathway also littered with many invisible milestones. These take the form of ideas, concepts, ambitions, hopes, habits, rituals, practices, institutions, and stories—the building blocks of culture and history. The journey down this pathway reveals how, as our ancestors developed the capacity to master many new different skills, our remarkable purposefulness was honed to the point that we are now capable of finding meaning, joy, and deep satisfaction in activities like building pyramids, digging holes, and doodling. It also shows how the work they did and the skills they acquired progressively shaped their experience of, and interactions with, the world around them.

But it is the points where these two pathways converge that are most important in terms of making sense of our contemporary relationship with work. The first of these points of convergence comes when humans mastered fire possibly as long as a million years ago. In learning how to outsource some of their energy needs to flames, they acquired the gift of more time free from the food-quest, the means to stay warm in the cold, and the ability to vastly extend their diets, so fueling the growth of ever more energy-hungry, harder-working brains.

The second crucial point of convergence was far more recent, and arguably far more transformative. It began some 12,000 years ago when some of our ancestors began to routinely store food and experiment with cultivation, transforming their relationships with their environments, with each other, with scarcity, and with work. Exploring this point of convergence also reveals how much of the formal economic architecture around which we organize our working lives today had its origins in farming and how intimately our ideas about equality and status are bound into our attitudes to work.

A third point of convergence occurs when people began to gather in cities and towns. This was around 8,000 years ago, when some agricultural societies started to generate big enough food surpluses to sustain large urban populations. And it too represents a major new chapter in the history of work—one defined not by the need to capture energy by working in the fields, but rather by the demands of spending it. The birth of the first cities seeded the genesis of a whole new range of skills, professions, jobs, and trades that were unimaginable in subsistence farming or foraging societies.

The emergence of large villages, then towns, and finally cities also played a vital role in reshaping the dynamics of the economic problem and scarcity. Because most urban people's material needs were met by farmers who produced food in the countryside, they focused their restless energy in pursuit of status, wealth, pleasure, leisure, and power. Cities quickly became crucibles of inequality, a process that was accelerated by the fact that within cities people were not bound together by the same intimate kinship and social ties that were characteristic of small rural communities. As a result, people living in cities increasingly began to bind their social identity ever more tightly to the work they did and find community among others who pursued the same trade as them.

The fourth point of convergence is marked by the appearance of factories and mills belching smoke from great chimneys as populations in Western Europe learned to unlock ancient stores of energy from fossil fuels and transform them into hitherto unimaginable material prosperity. At this point, which begins early in the eighteenth century, both pathways expand abruptly. They become more crowded, accommodating the rapid growth in the number and size of cities, a surge in the population of both humans and the animal and plant species our ancestors domesticated. They also become far busier as a result of the turbocharging of our collective preoccupation with scarcity and work—paradoxically as a result of there being more stuff than ever before. And while it is still too early tell, it is hard to avoid the suspicion that future historians will not distinguish between the first, second, third, and fourth industrial revolutions, but will instead consider this extended moment as critical as any other in our species' relationship with work.

PART ONE

In the Beginning

1

TO LIVE IS TO WORK

On this particular afternoon in the spring of 1994, it was so hot that even the children with their rawhide feet winced as they darted across the sand from one patch of shade to the next. There was no breeze and the dust clouds kicked up by the missionary's Land Cruiser as it thundered up the rough sand track toward the Skoonheid Resettlement Camp in Namibia's Kalahari Desert hung in the air long after the vehicle had come to a halt.

For the nearly 200 Ju/'hoansi Bushmen sheltering from the sun, occasional visits from missionaries were a welcome break from the monotony of waiting for government food handouts. They were also far more entertaining than traipsing across the desert from one vast cattle ranch to the next in the hope of persuading a white farmer to give them some work. Over the preceding half-century of living under the whip of the ranchers who had robbed them of their land, even the most skeptical among this community—the remnants of the most enduring hunter-gatherer society on earth—had come to believe it was common sense to pay attention to the ordained emissaries of the farmers' God. Some even found comfort in their words.

As the sun dropped toward the western horizon, the missionary climbed out of his Land Cruiser, set up an improvised pulpit at the base of the tree trunk, and summoned the congregation. It was still meltingly hot, and they sluggishly convened in the dappled shade of the tree. The only drawback of this arrangement was that, as the sun fell lower, the congregation had to periodically rearrange itself to remain in the shade, a process that involved much getting up, sitting down, elbowing, and nudging. As the service progressed and the tree's shadow lengthened, the majority of the congregation shifted progressively further and further away from the pulpit, forcing the missionary to deliver much of his sermon in a sustained bellow.

The setting added a certain biblical gravitas to the proceedings. Not only did the sun provide the missionary with a squint-inducing halo, but like the moon that would soon rise in the east and the tree the congregation sat beneath, the sun had a starring role in the tale he had to tell: Genesis and the Fall of Man.

The missionary began by reminding his congregation that the reason why people came together to worship every Sunday was because God had worked tirelessly for six days to make the heavens, earth, oceans, sun, moon, birds, beasts, fish, and so on, and only rested on the seventh day when his work was done. He reminded them that because humans were created in His image, they too were expected to toil for six days and on the seventh to rest, and offer gratitude for the uncountable blessings that the Lord had bestowed upon them.

The missionary's opening declaration generated some head nodding as well as an amen or two from the more enthusiastic congregation members. But most found it a challenge to identify exactly what blessings they should be grateful for. They knew what it meant to work hard, and they understood the importance of having time to rest, even if they had no idea how it felt to share in the material rewards of their labors. Over the preceding half century, it was their hands that did the heavy lifting that transformed this semi-arid environment into profitable cattle ranches. And over this period the farmers, who were otherwise not shy of using the whip to "cure" Ju/'hoan workers of idleness, always gave them time off on Sundays.

The missionary then told his congregation how after the Lord had instructed Adam and Eve to care for the Garden of Eden they were seduced by the serpent into committing mortal sin, as a result of which the Almighty "cursed the ground" and banished the sons and daughters of Adam and Eve to a life of toil in the fields.

This particular Bible story made more sense to the Ju/'hoansi than many others the missionaries told them—and not just because they all knew what it meant to be tempted to sleep with people they knew they shouldn't. In it they saw a parable of their own recent history. All the old Ju/'hoansi at Skoonheid remembered when this land was their sole domain and when they lived exclusively by hunting for wild animals and gathering wild fruits, tubers, and vegetables. They recalled that back then, like Eden, their desert environment was eternally (if temperamentally) provident and almost always gave them enough to eat on the basis of a few, often spontaneous, hours' effort. Some now speculated that it must have been as a result of some similar mortal sin on their part that, starting in the 1920s, first a trickle then a flood of white farmers and colonial police arrived in the Kalahari with their horses, guns, water pumps, barbed wire, cattle, and strange laws, and claimed all this land for themselves.

For their part, the white farmers quickly learned that farming in an environment as hostile to large-scale agriculture as the Kalahari would take a lot of labor. So they formed commandos to capture and force into work the "wild" Bushmen, held Bushman children hostage to ensure their parents' obedience, and meted out regular whippings to teach them the "virtues of hard work." Deprived of their traditional lands, the Ju/'hoansi learned that to survive, like Adam and Eve, they must toil on farms.

For thirty years, they settled into this life. But when in 1990 Namibia gained its independence from South Africa, technological advances meant that the farms were both more productive and less dependent on labor than they had been. And with a new government demanding that ranchers treat their Ju/'hoan laborers as formal employees and provide them with proper salaries and housing, many farmers simply chased them from their land. They reasoned that it was far more economical and far less trouble to invest in the right machinery and run their farms with as few staff as possible. As a result, many Ju/'hoansi had little option but to camp by the side of the road, squat in the fringes of Herero villages to the north, or move to one of the two small resettlement areas where there was little to do but sit and wait for food aid.

This is where the story of the fall ceased to make much sense to the Ju/'hoansi. For if, like Adam and Eve, they were banished by God to a life of toil in the fields, why had they now been banished from the fields by farmers who said they no longer had any use for them?

* * *

Sigmund Freud was convinced that all the world's mythologies—including the biblical story of Adam and Eve—held within them the secrets to the mysteries of our "psycho-sexual development." By contrast, his colleague and rival Carl Gustav Jung considered myths to be nothing less than the distilled essence of humanity's "collective unconscious." And to Claude Lévi-Strauss, the intellectual touchstone of much twentieth-century social anthropology, all the world's mythologies combined to form an immense and intricate puzzle box that if properly decoded would reveal the "deep structures" of the human mind.

The diverse mythologies of the world may or may not offer us a window into our "collective unconscious," explain our sexual hang-ups, or let us peer into the deep structures of our minds. But there is no doubt that they reveal some things that are universal to human experience. One is the idea that our world—no matter how perfect it was at the moment of creation—is subject to chaotic forces and that humans must work to keep these in check.

Among the missionary's congregation at Skoonheid that hot afternoon were a handful of "old-time people." They were the last Ju/'hoansi here to have spent much of their lives as hunter-gatherers. They bore the trauma of being violently wrenched from their old lives with the kind of stoicism that characterized traditional hunter-gatherer life, and as they awaited death they found comfort in retelling one another the "stories of the beginning"—the Creation myths—they learned as children.

Before Christian missionaries showed up with their own version of the tale, the Ju/'hoansi believed the creation of the world happened in two distinct phases. In the first phase their creator God made himself, his wives, a lesser trickster god called G//aua, the world, rain, lightning, holes in the ground that collected rainwater, plants, animals, and finally people. But before completing the job, he spent time on something else, leaving the unfinished world in a state of chaotic ambiguity. There were no social rules, no customs, and people and animals alike shape-shifted from one bodily form to another, variously intermarrying and eating one another as well as engaging in all sorts of outlandish behavior. Fortunately, the creator didn't abandon his creation forever and eventually returned to finish the job. He did so by imposing rules and order on the world, first by separating and naming the different species and then by endowing each with its own customs, rules, and characteristics.

The "stories of the beginning" that delighted the old men of Skoonheid are all set during the period when the creator, leaving his work incomplete, took his extended cosmic sabbatical—perhaps, as one man suggested, because he needed to take a rest just as the Christian God did. Most of these stories tell of how in the creator's absence the trickster thrived, causing mayhem and chaos wherever he went. In one story, for example, G//aua cuts out, cooks, and serves his own anus to his family, and laughs hysterically at the brilliance of his own joke when they compliment him on the tastiness of the dish. In others, he cooks and eats his wife, rapes his mother, steals children from their parents, and callously commits murder.

But G//aua did not rest when the creator returned to finish his work, and ever since has picked mischievously and unrelentingly at the world's orderly seams. Thus where the Ju/'hoansi associated the creator God with order, predictability, rules, manners, and continuity, G//aua was associated with randomness, chaos, ambiguity, discord, and disorder. And the Ju/'hoansi detected G//aua's devilish hand at work in all sorts of different things. They noticed it, for instance, when lions behaved uncharacteristically; when someone fell mysteriously ill; when a bowstring frayed or a spear snapped; or when they were persuaded by a mysterious inner voice to sleep with someone else's spouse while being only too aware of the discord this would cause.

The old-time people were in no doubt that the serpent who tempted Adam and Eve in the missionary's story was none other than their trickster G//aua in one of his many disguises. Spreading lies, persuading people to embrace forbidden desires, and then cheerfully witnessing the life-shattering consequences play out was exactly the sort of thing G//aua liked to do.

Ju/'hoansi are but one of many peoples to have discovered their own cosmic troublemakers lurking beneath the skin of Eden's smooth-talking serpent. Tricksters, troublemakers, and destroyers—like Odin's wayward son Loki, the coyote and raven in many indigenous North American cultures, or Anansi, the short-tempered, shape-shifting spider that scuttles through many West African and Caribbean mythologies—have been creating work for people to do since the beginning of time.

It is no coincidence that tension between chaos and order is a feature of the world's mythologies. After all, science also insists that there is a universal relationship between disorder and work, one that was first revealed during the heady days of the Enlightenment in Western Europe.

* * *

Gaspard-Gustave Coriolis loved the game of table billiards—a hobby to which he devoted many happy hours of practical "research," the results of which he published in the *Théorie mathématique des effets du jeu de billiard*, a book still invoked with biblical solemnity by aficionados of billiards' descendants, snooker and pool. He was born in the revolutionary summer of 1792, the same year that France’s Citizens’ Assembly abolished the monarchy and dragged King Louis XVI and Marie Antoinette from the Palace of Versailles to await their appointment with the guillotine. But Coriolis was a revolutionary of a different sort. He was one of the vanguard of men and women who had turned their back on theological dogma and instead embraced reason, the explanatory power of mathematics, and the rigor of the scientific method to make sense of the world, and who as a result ushered in the industrial age after unlocking the transformative energy of fossil fuels.

Coriolis is now best remembered for formulating the “Coriolis Effect,” without which meteorologists would have no sensible way of modeling the swirling forms of weather systems or the vagaries of ocean currents. More importantly for us he is also remembered for introducing the term “work” into the lexicon of modern science.

Coriolis’s interest in table billiards extended beyond the satisfaction he gained from the predictable click-clack of ivory balls as they collided with one another, or even the thrill he experienced when one, guided by his cue, slipped off the table into a pocket. To him, billiards revealed the infinite explanatory power of mathematics, and the billiard table was a space where people like him could observe, tinker, and play with some of the fundamental laws that governed the physical universe. Not only did the balls evoke the celestial bodies whose movements were described by Galileo, but every time he rested his billiard cue on his hand, he channeled the elemental principles of geometry as outlined by Euclid, Pythagoras, and Archimedes. And every time his cue ball, energized by the movement of his arm, struck other balls, they diligently followed the laws on mass, motion, and force identified by Sir Isaac Newton nearly a century earlier. They also raised a whole range of questions about friction, elasticity, and the transfer of energy.

Unsurprisingly, Coriolis’s most important contributions to science and mathematics focused on the effects of motion on rotating spheres: the kinetic energy an object like a billiard ball possesses due to its motion, and the process by which energy is transferred from an arm and through a cue to send billiard balls scuttling around the table.

It was in 1828, when describing a version of the latter phenomenon, that Coriolis first introduced the term “work” to describe the force that needed to be applied to move an object over a particular distance.[1]

When Coriolis referred to the process of hitting a billiard ball as doing “work,” he was, of course, not focused singularly on billiards. The first economically viable steam engines had been invented a few years previously, showing that fire was capable of much more than charring meat and melting iron in a smithy's forge. Yet there was no satisfactory way of evaluating the capabilities of the steam engines that were powering Europe's Industrial Revolution. Coriolis wanted to describe, measure, and compare accurately the capabilities of things like water wheels, cart horses, steam engines, and human beings.

By then many other mathematicians and engineers had already arrived at concepts broadly equivalent to what Coriolis called "work." But none had quite found the right vocabulary to describe it. Some called it "dynamical effect," others "laboring force," and others still "motive force."

Coriolis's equations were quickly pronounced sound by his scientific peers, but it was his terminology that impressed them most. It was as if he had found the perfect word to describe a concept that had teased them for years. Over and above the fact that "work" described exactly what steam engines were designed to do, the French word for work, *travail*, has a poetic quality that is absent in many other languages. It connotes not just effort but also suffering, and so evoked the recent tribulations of France's Third Estate—the lower classes—that had labored for so long under the yoke of wigged aristocrats and monarchs with a taste for grandeur. And in linking the potential of machines to liberate the peasantry from a life of labor, he invoked an embryonic version of the dream, later taken up by John Maynard Keynes, of technology leading us to a promised land.

"Work" is now used to describe all transfers of energy, from those that occur on a celestial scale when galaxies and stars form to those that take place at a subatomic level. Science also now recognizes that the creation of our universe involved colossal amounts of work, and that what makes life so extraordinary and what differentiates living things from dead things are the very unusual kinds of work that living things do.

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Living things have a number of distinct characteristics that non-living things do not. The most obvious and important of these is that living things actively harvest and use energy to organize their atoms and molecules into cells, their cells into organs, and their organs into bodies; to grow and to reproduce; and when they stop doing that they die and, with no energy to hold them together, they decompose. Put another way, to live is to work.

The universe hosts a bewildering array of complex and dynamic systems—from galaxies to planets—that we sometimes also describe as being “alive.” But, besides cellular organisms, none of these purposively harvest energy from other sources and then use that to do work to stay alive and reproduce. A “living” star, for instance, does not actively replenish its energy from its environment. Nor does it seek to produce offspring that will in time grow up to be just like it. Rather it fuels the work it does by destroying its own mass, and “dies” once that mass is depleted.

Life actively works to survive, grow, and reproduce potentially in spite of what some physicists consider to be the “supreme law of the universe”: the second law of thermodynamics, also known as the law of entropy. The second law of thermodynamics describes the tendency for all energy to distribute itself evenly across the universe. Embodied in the many tricksters that have made mischief in the world’s mythologies, entropy relentlessly unpicks whatever order the universe creates. And in time, like the malevolent trickster god Loki of Norse mythology, the second law of thermodynamics insists that entropy will bring about an Armageddon—not because it will destroy the universe but rather because, when it achieves its goal of distributing all energy evenly across the universe, no free energy will be available with the result that no work, in the physical sense of the word, can be done.

If we have an intuitive grasp of some aspects of entropy, it is because this trickster winks at us from every shadow. We see it in the decay of our buildings and our bodies, in the collapse of empires, in the way milk blends into our coffee, and in the constant effort required to maintain any kind of order in our lives, our societies, and our world.

* * *

For the pioneers of the Industrial Revolution, entropy revealed itself by thwarting their efforts to build perfectly efficient steam engines.

In all their experiments, they observed that heat energy inevitably tended to distribute itself evenly within boilers and then through the boilers’ metal skins to the world outside. They also noticed that heat energy always flowed from hotter to colder bodies and that once the heat was distributed evenly, it was impossible to reverse the process without adding more energy. This is why once a cup of tea has reached room temperature there is no chance of it drawing some energy out of the room to warm itself up again. They also noted that in order to reverse entropy's impact, more work needed to be done using energy sourced from outside that system. Bringing your tea back to an acceptable temperature requires additional energy.

For a while, the law of entropy was considered to be a bewildering fact of existence. Then, between 1872 and 1875, an Austrian physicist, Ludwig Boltzmann, worked the numbers. He showed that the way heat behaved could be neatly described by means of the arithmetic of probability.[2] There are, he argued, infinitely more ways for heat to be spread among the trillions of molecules in a spoonful of water than for the heat to remain stored in just a few of those particles. This means that as the particles move around and interact with one another, the odds are so overwhelmingly in favor of the energy being evenly distributed that it has to be considered inevitable. By extension, his mathematical model suggested that all the energy in the largest container of all, the universe, will tend to do the same.

In offering a mathematical model to describe entropy, Boltzmann simultaneously engineered its escape from the relatively narrow confines of engineering and showed us why we intuitively see entropy in decaying buildings, eroding mountains, exploding stars, spilled milk, death, cold cups of tea, and even democracy.

States of low entropy are "highly ordered," like children's bedrooms when the children are forced to tidy up and stow their toys, gadgets, clothes, books, and tubs of slime in assorted drawers and cupboards. States of high entropy, by contrast, are similar to their rooms a few hours later, once the children have picked up and then dropped everything they own seemingly at random. According to Boltzmann's calculations, every possible arrangement of a kid's stuff in their rooms is equally probable in a physical sense if children, as it appears is the case, are nothing more than random-stuff redistributors. There is of course a minuscule chance that, as random-stuff redistributors, they might accidentally put all their things back where they are supposed to be for the rooms to be considered tidy. The problem is that there are vastly more ways for the rooms to be messy than there are for them to be tidy, so the chances are hugely in favor of their rooms being messy until a parent demands they do the work—and so expend the energy necessary—to restore their rooms to an acceptably low state of entropy.

Even if there are many orders of magnitude simpler than a child's bedroom, the now venerable Rubik's cube gives us a sense of the mathematical scales involved. This puzzle, with its six different-colored faces made up of nine squares and organized on a fixed central pivot that makes it possible to rotate any one of the faces independently of the others and so mix up the colored squares, has 43,252,003,274,489,856,000 possible unsolved states and only one solved state.[3]

* * *

In 1886, four years after Charles Darwin was buried in Westminster Abbey, Boltzmann was invited to deliver a prestigious public lecture at the Imperial Academy of Sciences in Vienna.

"If you ask me about my innermost conviction whether our century will be called the century of iron or the century of steam or electricity," Boltzmann announced to his audience, "I answer without hesitation: it will be called the century of the mechanical view of nature, the century of Darwin."[4]

A generation younger than Darwin, Ludwig Boltzmann's work was no less a challenge to God's authority than Darwin's proposal that it was evolution rather than God that best accounted for the diversity of life. In a universe governed by the laws of thermodynamics, there was no room for God's commandments, and the ultimate destiny of everything was predetermined.

Boltzmann's admiration for Darwin was not based solely on their shared experience of taking wrecking balls to religious dogma. It was also because he saw entropy's hand busily shaping evolution, an idea that would only be fully fleshed out a generation later by the Nobel Prize–winning quantum physicist Erwin Schrödinger, best known for packing imaginary cats into imaginary boxes.

Schrödinger was convinced that the relationship between life and entropy was fundamental. Others before him, including Boltzmann, had made the point that living organisms were all thermodynamic engines: like steam engines they required fuel in the form of food, air, and water to work, and in working they also converted some of this fuel into heat that was subsequently lost to the universe. But no one followed this idea to its inevitable conclusion until Schrödinger presented a series of lectures to an audience at Trinity College Dublin in 1943.

Schrödinger's father was an enthusiastic amateur gardener. He was especially fascinated by the way he could tip evolution's hand by carefully selecting seeds of plants with specific characteristics he found desirable. Inspired by his father's horticultural experiments, Schrödinger retained an interest in heredity and evolution that endured long after theoretical physics became the main focus of his work.

Before Schrödinger delivered his Dublin lectures, which were published a year later in the form of a short book called *What Is Life?*, biology was an orphan among the natural sciences.[5] Up until then, most scientists were content to accept that life operated according to its own strange and distinctive rules. Schrödinger, however, was of the view that biology should be adopted as a fully fledged member of the scientific family. That night, he set out to persuade his audience that the science of life—biology—was just another, admittedly complex, branch of physics and chemistry. Just because physicists and chemists had not yet been able to explain life, he explained to his audience, it did not mean that there was any "reason at all for doubting" that they could.

Schrödinger's description of what he imagined to be the extraordinary information-encoding and instruction-giving capabilities of the atoms and molecules in our cells—DNA and RNA—inspired a generation of scientists to dedicate their careers to unraveling the chemical and physical bases of biology. Among this pioneering group of molecular biologists was Cambridge's Francis Crick who, along with his partner James Watson, would reveal the distinctive double-helix shape of DNA to the world a decade later.

Schrödinger's wonder for the ability of the "incredibly small group of atoms"[6] that comprise a genome to organize trillions of other atoms into hair, livers, fingers, eyeballs, and so on was because these atoms did so in apparent defiance of the second law of thermodynamics. Unlike almost everything else in the universe, which seemed to tend toward increasing disorder, life insolently gathered matter together and then organized it very precisely into astonishingly complex structures that gathered free energy and reproduced.

But as much as living organisms appeared to be only superficially accomplished and systematic violators of the law of entropy, Schrödinger recognized that life simply could not exist in violation of the second law of thermodynamics. This meant that life needed to contribute to the overall entropy in the universe, and he concluded that it did this by seeking out and capturing free energy, using it to do work, which generated heat, and thus added to the total entropy in the universe. He also noted that the bigger and more complex an organism, the more work it needed to stay alive, grow, and reproduce, and that as a result, complex structures, like living organisms, were often far more energetic contributors to the total entropy of the universe than objects like rocks.

If life can be defined by the kinds of work living things do, then the process of transforming inorganic terrestrial matter into living, organic matter must have involved some kind of work—an energy-packed jump-start that set the engine of primordial life running. Precisely where this energy came from is uncertain. It may have sprung from the finger of God, but far more likely it was sourced from the geochemical reactions that made early earth seethe and fizz, or by the decay of radioactive materials in ancient earth succumbing slowly to entropy.

The fact that abiogenesis—the process by which life first appeared—involved work is perhaps the least mysterious part of it. Up until the turn of the third millennium, the balance of scientific data suggested that the emergence of life was so improbable that we were almost certainly alone in the universe. Now, for some scientists at least, the pendulum has swung the other way. They are more inclined to think that life may have been inevitable and that entropy, the trickster god, was not just a destroyer but may well have also been the creator of life. This perspective is based on the idea that biological systems might suddenly emerge because they more efficiently dissipate heat energy than many inorganic forms, so adding to the total entropy of the universe.[7]

One of the things that persuaded some of them was digital simulations that indicated that where atoms and molecules are subjected to a highly directed energy source (like the sun) and are also surrounded by an energy bath (like a sea), particles will spontaneously arrange themselves in all sorts of different formations, as if experimenting to find the arrangement that dissipates heat energy most effectively.[8] If this is the case, this model suggests, then there is a pretty good chance that one of the countless possible arrangements the atoms and molecules shuffle through might be one that transforms dead inorganic matter into a living organism.

The long history of life on earth has been described in terms of life's ability to capture energy from new sources—first geothermal energy, then sunlight, then oxygen, and then the flesh of other living organisms—as well as the evolution of increasingly complex, more energy-hungry, and, in the physical sense, harder-working life forms.[9]

The first living creatures on planet Earth were almost certainly simple single-celled organisms that, like bacteria, had neither nuclei nor mitochondria. They probably harvested energy from geochemical reactions between water and rock, before transducing it into a highly specialized molecule that stored the energy in its chemical bonds and released it when those bonds were broken, so enabling the organism to do work. This molecule, adenosine triphosphate, or "ATP," is the immediate source of energy used by all cells to do work—from unicellular bacteria to multicellular anthropologists—to maintain their internal equilibrium, to grow and to reproduce.

Life has been busy harvesting free energy, storing it in ATP molecules, and then putting it to work on our planet for a very long time. There is widespread fossil evidence attesting to the presence of bacterial life on earth around 3.5 billion years ago. There is also disputed fossil evidence for life dating to 4.2 billion years ago—a mere 300,000 years after the earth's formation.

The bacteria-like pioneers of life on earth had to cope with conditions that, from the point of view of most life forms now, were astonishingly hostile. Beyond the fact that early earth was seething with volcanic activity and battered by a near-continuous barrage of meteorites, the atmosphere had little oxygen and no ozone layer to protect delicate organisms from being fried by solar radiation. As a result, earth's earliest life forms toiled far from the sun's glare.

But, over time, thanks to another characteristic unique to life, its ability to evolve, new species emerged that were capable of drawing energy from other sources, and surviving and reproducing in different conditions. At some point, probably around 2.7 billion years ago, life crept out from the shadows as a series of fortuitous genetic mutations enabled some to embrace life's old enemy, sunlight, and draw energy from it by means of photosynthesis. These organisms, cyanobacteria, still thrive today. We see them in the bacterial blooms that bubble up in ponds and lakes.

As cyanobacteria flourished, so they set to work transforming the earth into a macro-habitat capable of supporting far more complex life forms with much higher energy demands. They did so first by converting atmospheric nitrogen into organic compounds like nitrates and ammonia, which plants need for their growth. They also worked to convert carbon dioxide into oxygen and so played the critical role in inducing “the great oxidation event” that began around 2.45 billion years ago, and which resulted in the gradual creation of the oxygen-rich atmosphere that sustains us today.

The great oxidation event not only provided an entirely new source of energy for life to exploit, but massively expanded the amount of energy available for life to work with. Chemical reactions involving oxygen release far more energy than those involving most other elements, which means that individual aerobic (oxygen-breathing) organisms have the potential to grow bigger, faster, and do much more physical work than anaerobic ones.

New, more elaborate living organisms called eukaryotes evolved to exploit this energy-rich environment. Far more sophisticated and energy-hungry than their prokaryotic ancestors, eukaryotes had nuclei, reproduced by means of sexual reproduction, and could also generate all sorts of complex proteins. In time, some eukaryotes are thought to have developed mutations that enabled them to kidnap other passing life forms and plunder their energy by engulfing them through permeable outer cell membranes. The kidnapped cells had no choice but to share any energy they had captured with their jailers, one of the processes that, over time, is thought to have contributed to the emergence of multicellular life. The primitive algae, which evolved into the first plants that eventually greened early earth’s barren land masses, were likely to have been the progeny of cyanobacteria-kidnapping eukaryotes.

The first creatures with both tissue and proper nervous systems are thought to have evolved in the oceans around 700 million years ago. But it was not until around 540 million years ago during the Cambrian explosion that animal life really started to flourish. The fossil record for this period shows evidence of creatures representing all the major contemporary phyla—branches on the tree of life—that populate our world today.

Additional energy from increasing atmospheric and marine oxygen certainly played a role in kick-starting the Cambrian explosion. But what likely played a more important role was that evolution began to positively select in favor of some life forms that harvested their energy from a novel, much richer source of free energy than oxygen: they consumed other living things that had already gone to the trouble of collecting and concentrating energy and vital nutrients in their flesh, organs, shells, and bones.

By around 650 million years ago, enough atmospheric oxygen had accumulated in the stratosphere to form a layer of ozone sufficiently thick to screen out enough hazardous ultraviolet radiation to allow some life forms to make a living on the fringes of the oceans without being fried. Within 200 million years or so, the biosphere laid claim to much of the earth's land mass and slowly formed a series of connected, very complex marine and terrestrial ecosystems packed with all sorts of organisms diligently capturing free energy and using it to stay alive, secure more energy, and reproduce.

Many of these new life forms put this energy to use in ways that far more obviously look like the kinds of behaviors we humans associate with work. While bacteria still comprised a substantial portion of the biosphere, the presence of larger land-based animals transformed the nature of work that living things did. Larger animals require lots of food but can do far more physical work than relatively immobile microorganisms. Animals variously burrow, hunt, flee, break, dig, fly, eat, fight, defecate, move things about, and, in some cases, build.

The fact that from a physicist's perspective all living organisms do work, and that our planet's biosphere was constructed over millions of generations as a result of the work done by their various evolutionary ancestors, raises an obvious question: How does the work done, for example, by a tree, a cuttlefish, or a zebra, differ from that which has brought our species to the cusp of creating artificial intelligence?

2

IDLE HANDS AND BUSY BEAKS

Unusually for a Californian celebrity, Koko did not worry a great deal about her appearance. In 2016, when she passed away, nearly two years after delivering a special address to the UN Climate Change Conference warning of how human folly might lead us to oblivion, many prominent Californians expressed pride in the achievements of one of their state's beloved daughters.

A lowland gorilla that had known only captivity, Koko owed her celebrity to her unusual communication skills. She was a fluent and creative user of Gorilla Sign Language, a specially designed gestural language based roughly on American Sign Language. She also gave every indication of understanding around 2,000 distinct spoken English words, about 10 percent of the active vocabulary most humans use. But Koko was terrible at grammar. Attempts to school her in the rudiments of syntax confused and frustrated her, and as a result, she often struggled to communicate with the kind of clarity or creativity her trainers believed she wanted to. Beyond her syntactical shortcomings, Koko's human trainers entertained no doubts that Koko was an emotionally and socially sophisticated individual.

"She laughs at her own jokes and those of others," explained Penny Patterson and Wendy Gordon, two of her long-term trainers and most beloved friends. "She cries when hurt or left alone, screams when frightened or angered. She talks about her feelings, using words such as happy, sad, afraid, enjoy, eager, frustrate, mad, shame and, most frequently, love. She grieves for those she has lost—a favorite cat that has died, a friend who has gone away. She can talk about what happens when one dies, but she becomes fidgety and uncomfortable when asked to discuss her own death or the death of her companions. She displays a