VIVEK WADHWA with ALEX SALKEVER

THE DRIVER IN THE DRIVERLESS CAR

HOW OUR TECHNOLOGY CHOICES WILL CREATE THE FUTURE

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PREFACE

Not long ago, I was very pessimistic about the future. I was worried about hunger and poverty, disease, overpopulation. I believed that the world would run out of clean water and energy and that we would be fighting world wars over scarce resources.

Today, I talk about this being the greatest period in history, when we will solve the grand challenges of humanity and enter an era of enlightenment and exploration such as we saw in my favorite TV series, *Star Trek*. Yes, I grew up dreaming of tricorders, replicators, and androids and wanting to be an astronaut so that I could join Starfleet Academy. Didn't all the people from my generation, of the '60s?

At Stanford, Duke, and Singularity universities, and now at Carnegie Mellon, I have spent the past six years researching the advances in technology that are finally making science fiction a reality. It truly is amazing what is possible, as I will explain in this book. But I have come to realize that reaching Utopia will take vigilance and effort: like the course of a game of snakes and ladders, our path is strewn with hazards.

My research has made me acutely aware of the dangers in advanced technologies. These are moving faster than people can absorb change—and offer both unprecedented rewards and unpredictable hazards.

As a society, we can make amazing things happen; and the more we understand, the better our decision making will be—and the greater the odds that we head toward *Star Trek*. Today's technology changes are happening so quickly and are so overwhelming that all of us—including technologists—can benefit from access to new tools for considering and managing them. I wrote this book with the help of my good friend and writing guru, Alex Salkever, in order to provide such tools, because I believe in the power of choice and the greater judgment of involved citizens. We hope that it will help you deal with the challenges that new technologies raise now and in the future.

INTRODUCTION

It is a warm autumn morning, and I am walking through downtown Mountain View, California, when I see it. A small vehicle that looks like a cross between a golf cart and a Jetsonesque bubble-topped spaceship glides to a stop at an intersection. Someone is sitting in the passenger seat, but no one seems to be sitting in the driver seat. How odd, I think. And then I realize I am looking at a Google car. The technology giant is headquartered in Mountain View, and the company is road-testing its diminutive autonomous cars there.

This is my first encounter with a fully autonomous vehicle on a public road in an unstructured setting.

The Google car waits patiently as a pedestrian passes in front of it. Another car across the intersection signals a left-hand turn, but the Google car has the right of way. The automated vehicle takes the initiative and smoothly accelerates through the intersection. The passenger, I notice, appears preternaturally calm.

I am both amazed and unsettled. I have heard from friends and colleagues that my reaction is not uncommon. A driverless car can challenge many assumptions about human superiority to machines.

Though I live in Silicon Valley, the reality of a driverless car is one of the most startling manifestations of the future unknowns we all face in this age of rapid technology development. Learning to drive is a rite of passage for people in materially rich nations (and becoming so in the rest of the world): a symbol of freedom, of power, and of the agency of adulthood, a parable of how brains can overcome physical limitations to expand the boundaries of what is physically possible. The act of driving a car is one that, until very recently, seemed a problem only the human brain could solve.

Driving is a combination of continuous mental risk assessment, sensory awareness, and judgment, all adapting to extremely variable surrounding conditions. Not long ago, the task seemed too complicated for robots to handle. Now, robots can drive with greater skill than humans—at least on the highways. Soon the public conversation will be about whether humans should be allowed to take control of the wheel at all.

This paradigm shift will not be without costs or controversies. For sure, widespread adoption of autonomous vehicles will eliminate the jobs of the millions of Americans whose living comes of driving cars, trucks, and buses (and eventually all those who pilot planes and ships). We will begin sharing our cars, in a logical extension of Uber and Lyft. But how will we handle the inevitable software faults that result in human casualties? And how will we program the machines to make the right decisions when faced with impossible choices—such as whether an autonomous car should drive off a cliff to spare a busload of children at the cost of killing the car's human passenger?

I was surprised, upon my first sight of a Google car on the street, at how mixed my emotions were. I've come to realize that this emotional admixture reflects the countercurrents that the bow waves of these technologies are rocking all of us with: trends toward efficiency, instantaneity, networking, accessibility, and multiple simultaneous media streams, with consequences in unemployment, cognitive and social inadequacy, isolation, distraction, and cognitive and emotional overload.

Once, technology was a discrete business dominated by business systems and some cool gadgets. Slowly but surely, though, it crept into more corners of our lives; today, that creep has become a headlong rush. Technology is taking over everything: every part of our lives, every part of society, every waking moment of every day. Increasingly pervasive data networks and connected devices are enabling rapid communication and processing of information, ushering in unprecedented shifts—in everything from biology, energy, and media to politics, food, and transportation—that are redefining our future. Naturally we're uneasy; we should be. The majority of us, and our environment, may receive only the backlash of technologies chiefly designed to benefit a few. We need to feel a sense of control over our own lives; and that necessitates actually having some.

The perfect metaphor for this uneasy feeling is the Google car. We welcome a better future, but we worry about the loss of control, of pieces of our identity, and most importantly of freedom. What are we yielding to technology? How can we decide whether technological innovation that alters our lives is worth the sacrifice?

The noted science-fiction writer William Gibson, a favorite of hackers and techies, said in a 1999 radio interview (though apparently not for the first time): "The future is already here; it's just not very evenly distributed."[1] Nearly two decades later—though the potential now exists for most of us, including the very poor, to participate in informed decision making as to its distribution and even as to bans on use of certain technologies—Gibson's observation remains valid.

I make my living thinking about the future and discussing it with others, and am privileged to live in what to most is the future. I drive an amazing Tesla Model S electric vehicle. My house, in Menlo Park, close to Stanford University, is a Passive House, extracting virtually no electricity from the grid and expending minimal energy on heating or cooling. My iPhone is cradled with electronic sensors that I can place against my chest to generate a detailed electrocardiogram to send to my doctors, from anywhere on Earth.*

Many of the entrepreneurs and researchers I talk with about breakthrough technologies, such as artificial

*I have a history of heart trouble, including a life-threatening heart attack; my ability to communicate with my doctors in seconds instead of hours makes my life both safer and easier, and gives me the confidence to go hiking up mountains and to travel the world giving talks.

intelligence and synthetic biology, are building a better future at a breakneck pace. One team built a fully functional surgical-glove prototype to deliver tactile guidance for doctors during examinations—in three weeks. Another team's visualization software, which can tell farmers the health of their crops using images from off-the-shelf drone-flying video cameras, took four weeks to build.

The distant future, then, is no longer distant. Rather, the institutions we expect to gauge and perhaps forestall new technologies' hazards, to distribute their benefits, and to help us understand and incorporate them are drowning in a sea of change as the pace of technological change outstrips them.

The shifts and the resulting massive ripple effects will, if we choose to let them, change the way we live, how long we live, and the very nature of being human. Even if my futuristic life sounds unreal, its current state is something we may laugh at within a decade as a primitive existence—because our technologists now have the tools to enable the greatest alteration of our experience of life that we will have seen since the dawn of humankind. As in all other manifest shifts—from the use of fire to the rise of agriculture and the development of sailing vessels, internal-combustion engines, and computing—this one will arise from breathtaking advances in technology. It is far larger, though, is happening far faster, and may be far more stressful to those living through this new epoch. Inability to understand it will make our lives and the world seem even more out of control.

In the next few chapters, I will take you into this future, discussing some of the technologies that are advancing at an exponential pace and illustrating what they make possible. You will see how excited I am about their potential—and how worried, at the same time, about the risks that they create.

Broadly speaking, we will, jointly, choose one of two possible futures. The first is a utopian *Star Trek* future in which our wants and needs are met, in which we focus our lives on the attainment of knowledge and betterment of humankind. The other is a *Mad Max* dystopia: a frightening and alienating future, in which civilization destroys itself.

These are both worlds of science fiction created by Hollywood, but either could come true. We are already capable of creating a world of tricorders, replicators, remarkable transportation technologies, general wellness, and an abundance of food, water, and energy. On the other hand, we are capable too now of ushering in a jobless economy, the end of all privacy, invasive medical-record keeping, eugenics, and an ever worsening spiral of economic inequality: conditions that could create an unstable, Orwellian, or violent future that might undermine the very technology-driven progress that we so eagerly anticipate. And we know that it is possible to inadvertently unwind civilization's progress. It is precisely what Europe did when, after the Roman Empire, humanity slid into the Dark Ages, a period during which significant chunks of knowledge and technology that the Romans had hard won through trial and error disappeared from the face of the Earth. To unwind our own civilization's amazing progress will require merely cataclysmic instability.

It is the choices we all make that will determine the outcome. Technology will surely create upheaval and destroy industries and jobs. It will change our lives for better and for worse simultaneously. But we can reach *Star Trek* if we can share the prosperity we are creating and soften its negative impacts, ensure that the benefits outweigh the risks, and gain greater autonomy rather than becoming dependent on technology.

You will see that there is no black and white; the same technologies that can be used for good can be used for evil in a continuum limited only by the choices we make jointly. All of us have a role in deciding where the lines should be drawn.

At the end of the day, you will realize that I am an optimistic at heart. I sincerely believe that we will all learn, evolve, and come together as a species and do amazing things.

With that, let the journey begin.

PART ONE

The Here and Now

◆ 1 ◆

A Bitter Taste of Dystopia

The 2016 presidential campaign made everybody angry. Liberal Bernie Sanders supporters were angry at allegedly racist Republicans and a political system they perceived as being for sale, a big beneficiary being Hillary Clinton. Conservative Donald Trump supporters were furious at the decay and decline of America, and at how politicians on both sides of the aisle had abandoned them and left a trail of broken promises. Hillary Clinton supporters fumed at how the mainstream media had failed to hold Trump accountable for lewd behavior verging on sexual assault—and worse.

The same rage against the system showed up in Britain, where a majority of citizens primarily living outside of prosperous London voted to take England out of the European Union. In Germany, a right-wing party espousing a virulent brand of xenophobia gained critical seats in the Bundestag. And around the world in prosperous countries, anger simmered, stoked by a sense of loss and by raging income inequality. In the United States, real incomes have been falling for decades. Yet in the shining towers of finance and on kombucha-decked tech campuses for glittering growth engines such as Google and Apple, the gilded class of technology employees and Wall Street types continue to enjoy tremendous economic gains.

The roots of the rage are, in my opinion, traceable to the feelings of powerlessness that have been building since the incursion into our lives of the microprocessor and the computer. At first, we greeted computers with a sense of wonder. Simple things such as spreadsheets, word processors, and arcade-quality video games could be run on tiny boxes in our living rooms!

The technology wove deeper into our lives. E-mail replaced paper mail. Generations of Americans will never write a full letter by hand. Social networks reinstated lost connections and spread good tidings. Discussions flourished. Maps went from the glovebox to the smart phone, and then replaced our own sense of navigation with computer-generated GPS turn-by-turn guidance so prescient that neither I nor most of my friends can remember the last time we printed out directions to a party or a restaurant.

As the new electronics systems grew smarter, they steadily began to replace many human activities. Mind-numbing phone menu trees replaced customer-service reps. In factories, robots marched steadily inward, thinning the ranks of unskilled and semi-skilled human workers even as efficiency soared and prices of the goods produced plummeted. This happened not only in the United States but also in China and other cheap-labor locales; a robot costs the same in Shanghai or Stuttgart or Chicago.

And, around the time when computers first arrived, we began to experience a stubborn stagnation. Wages for the middle class seemed to remain depressed. The optimism of the baby-boomer era gave way to pessimism as the industrial heartlands hollowed out. Even the inevitable economic cycles seemed less forgiving. In the 1990s and early 2000s, the United States began to experience so-called jobless recoveries. In these frustrating episodes, though economic growth registered a strong bump, the number of jobs and wages remained flaccid in comparison with historical norms.

In the United States, a creeping fear grew with each generation that the promise of a life better than their parents' would go unfulfilled. Meanwhile, the computers and systems starting advancing at an exponential pace—getting faster, smaller, and cheaper. Algorithms began to replace even lawyers, and we began to fear that the computer was going to come for our job, someday, somehow—just wait.

As income inequality grew, the yawning gap pushed the vast majority of the benefits of economic growth in wages and wealth to the top 5 percent of the world's society. The top 1 percent reaped the biggest rewards, far out of proportion to their number.

None of this is to say that Americans are materially worse off than they were forty years ago. Today, we own more cars, our houses are larger, our food is fancier and cheaper. A supercomputer—the iPhone or latest Android model—fits in our back pocket. But human beings tune out these sorts of absolute gains and focus on changes in relative position. With that focus, a dystopian worldview is logical and perhaps inevitable. The ghost in the machine becomes a handful of culprits. Politicians fail us because they cannot turn back the clock to better times (which, in real terms, were actually poorer, more dangerous, and shorter-lived). The banks and other big businesses treat humans as pawns.

So it is the soulless technology that is taking away our jobs and our dignity. But we as individuals can help control and influence it. The public outcry[1] and e-mail deluge directed at the U.S. Congress over the Stop Online Piracy Act[2] and the Protect IP Act[3] are examples. Those laws sought to make it harder to share music and movies on line. A campaign mounted by millions of normal citizens to deluge Washington, D.C., with e-mails and phone calls overnight flipped politicians from pro to con, overcoming many millions of lobbying dollars by the entertainment industry.

Technology taken too far in the other direction, however, can bring out our worst Luddite impulses. The protesters flinging feces at the Google-buses in downtown San Francisco gave voice to frustration that rich techies are taking over the City by the Bay; but the protest was based on scant logic. The private buses were taking cars off the roads, reducing pollution, minimizing traffic, and fighting global warming. Could flinging feces at a Google-bus turn back the clock and reduce prices of housing to affordable levels?

The 2016 presidential campaign was the national equivalent of the Google-bus protests. The supporters of Donald Trump, largely white and older, wanted to turn back the clock to a pre-smartphone era when they could be confident that their lives would be more stable and their incomes steadily rising. The Bernie Sanders supporters, more liberal but also mostly white (albeit with great age diversity), wanted to turn back the clock to an era when the people, not the big corporations, controlled the government. We have seen violent protests in Paris and elsewhere against Uber drivers. What sorts of protests will we see when the Uber cars no longer have drivers and the rage is directed only at the machine itself?

So easily could the focus of our discontent turn to the technology and systems that hold the promise to take us to a life of unimaginable comfort and freedom. At the same time, as I discussed in the introduction, the very technology that holds this promise could also contribute to our demise. Artificial Intelligence, or A.I., is both the most important breakthrough in modern computing and the most dangerous technology ever created by man. Remarkably, in similar times in the past, humanity has time and again successfully navigated these difficult passages from one era to the next. The transitions have not come without struggle, conflict, and missteps, but in general they were successful once people accepted the future and sought to control it or at least make better-informed decisions about it.

This is the challenge we have ahead: to involve the public in making informed choices so that we can create the best possible future, and to find ways to handle the social upheaval and disruption that inevitably will follow.

2

Welcome to Moore's World

Parked on the tarmac of Heathrow Airport, in London, is a sleek airliner that aviation buffs love. The Concorde was the first passenger airliner capable of flying at supersonic speed. Investment bankers and powerful businessmen raved about the nearly magical experience of going from New York to London in less than three hours. The Concorde was and, ironically, remains the future of aviation.

Unfortunately, all the Concordes are grounded. Airlines found the service too expensive to run and unprofitable to maintain. The sonic boom angered communities. The plane was exotic and beautiful but finicky. Perhaps most important of all, it was too expensive for the majority, and there was no obvious way to make its benefits available more broadly. This is part of the genius of Elon Musk as he develops Tesla: that his luxury company is rapidly moving downstream to become a mass-market player. Clearly, though, in the case of the Concorde, the conditions necessary for a futuristic disruption were not in place. They still are not, although some people are trying, including Musk himself, with his Hyperloop transportation project.

Another anecdote from London: in 1990, a car service called Addison Lee launched to take a chunk out of the stagnant taxi market. The service allowed users to send an SMS message to call for the cab, and a software-driven, computerized dispatch system ensured that drivers would pick up the fare seeker anywhere in the city within minutes.[1] This is, of course, the business model of Uber. But Addison Lee is available only in London; its management has never sought to expand to new cities.

Addison Lee was most recently sold to private-equity firm Carlyle Group for an estimated £300 million.[2] In late 2016, Uber was valued at around $70 billion,[3] and there were predictions it would soon be worth $100 billion, two or three hundred times the worth of Addison Lee. That's because each of us can use the same Uber application in hundreds of cities around the world to order a cab that will be paid for by the same credit card, and we have a reasonable guarantee that the service will be of high quality. From day one, Uber had global ambition. Addison Lee had the same idea but never pursued the global market.

This ambition of Uber's extends well beyond cars. Uber's employees have already considered the implications of their platform and view Uber not as a car-hailing application but as a marketplace that brings buyers and sellers together. You can see signs of their testing the marketplace all the time, ranging from comical marketing ploys such as using Uber to order an ice-cream truck or a mariachi band, to the really interesting, such as "Ubering" a nurse to offer everyone in the office a flu vaccine. Uber's CEO, Travis Kalanick, openly claims that his service will replace car ownership entirely once self-driving car fleets enter the mainstream.[4] What will happen to the humans who drive for Uber today remains an open question.

So what makes conditions ripe for a leap into the future in any specific economic segment or type of service? There are variations across the spectrum, but a few conditions tend to presage such leaps. First, there must be widespread dissatisfaction, either latent or overt, with the status quo. Many of us loathe the taxi industry (even if we often love individual drivers), and most of us hate large parts of the experience of driving a car in and around a city. No one is totally satisfied with the education system. Few of us, though we may love our doctors, believe that the medical system is doing its job properly, and scary stats about deaths caused by medical errors—now understood to be the third-highest cause of fatality in the United States—bear out this view. None of us likes our electric utility or our cell-phone provider or our cable-broadband company in the way we love Apple or enjoy Ben & Jerry's ice cream. Behind all of these unpopular institutions and sectors lies a frustrating combination of onerous regulations, quasi-monopolistic franchises (often government sanctioned) or ownership of scarce real estate (radio spectrum, medallions, permits, etc.), and politically powerful special interests.

That dissatisfaction is the systemic requisite. Then there are the technology requisites. All of the big (and, dare I say, disruptive) changes we now face can trace their onset and inevitability to Moore's Law. This is the oft-quoted maxim that the number of transistors per unit of area on a semiconductor doubles every eighteen months. Moore's

Law explains why the iPhone or Android phone you hold in your hand is considerably faster than supercomputers were decades ago and orders of magnitude faster than the computers NASA employed in sending a man to the moon during the Apollo missions.

Disruption of societies and human lives by new technologies is an old story. Agriculture, gunpowder, steel, the car, the steam engine, the internal-combustion engine, and manned flight all forced wholesale shifts in the ways in which humans live, eat, make money, or fight each other for control of resources. This time, though, Moore's Law is leading the pace of change and innovation to increase exponentially.

Across the spectrum of key areas we are discussing—health, transport, energy, food, security and privacy, work, and government—the rapid decrease in the cost of computers is poised to drive amazing changes in every field that is exposed to technology; that is, in *every* field. The same trend applies to the cost of the already cheap sensors that are becoming the backbone both of the web of connected devices called the Internet of Things (I.o.T.) and of a new network that bridges the physical and virtual worlds. More and more aspects of our world are incorporating the triad of software, data connectivity, and handheld computing—the so-called technology triad—that enables disruptive technological change.

Another effect of this shift will be that any discrete analog task that *can* be converted into a networked digital one *will* be, including many tasks that we have long assumed a robot or a computer would never be able to tackle. Robots will seem human-like and will do human-like things.

A good proportion of experts in artificial intelligence believe that such a degree of intelligent behavior in machines is several decades away. Others refer often to a book by the most sanguine of all the technologists, noted inventor Ray Kurzweil. Kurzweil, in his book *How to Create a Mind: The Secret of Human Thought Revealed*, posits: "[F]undamental measures of information technology follow predictable and exponential trajectories."[5] He calls this hypothesis the "law of accelerating returns."[6] We've discussed the best-recognized of these trajectories, Moore's Law. But we are less familiar with the other critical exponential growth curve to emerge in our lifetime: the volume of digital information available on the Internet and, now, through the Internet of Things. Kurzweil measures this curve in "bits per second transmitted on the Internet." By his measure (and that of others, such as Cisco Systems), the amount of information buzzing over the Internet is doubling roughly every 1.25 years.[7] As humans, we can't keep track of all this information or even know where to start. We are now creating more information content in a single day than we created in decades or even centuries in the pre-digital era.

The key corollary that everyone needs to understand is that as any technology becomes addressable by information technology (i.e., computers), it becomes subject to the law of accelerating returns. For example, now that the human genome has been translated into bits that computers process, genomics becomes de facto an information technology, and the law of accelerating returns applies. When the team headed by biochemist and geneticist J. Craig Venter announced that it had effectively decoded 1 percent of the human genome, many doubters decried the slow progress. Kurzweil declared that Venter's team was actually halfway there, because, on an exponential curve, the time required to get from 0.01 percent to 1 percent is equal to the time required to get from 1 percent to 100 percent.

Applying this law to real-world problems and tasks is often far more straightforward than it would seem. Many people said that a computer would never beat the world's best chess grandmaster. Kurzweil calculated that a computer would need to calculate all possible combinations of the 100,000 possible board layouts in a game and do that rapidly and repeatedly in a matter of seconds. Once this threshold was crossed, then a computer would beat a human. Kurzweil mapped that threshold to Moore's Law and bet that the curves would cross in 1998, more or less. He was right.

To be clear, a leap in artificial intelligence that would make computers smarter than humans in so-called general intelligence is a task far different from and more complicated than a deterministic exercise such as beating a human at chess. So how long it will be until computers leap to superhuman intelligence remains uncertain.

There is little doubt, though, about the newly accelerating shifts in technology. The industrial revolution unfolded over nearly one hundred years. The rise of the personal computer spanned forty-five years and still has not attained full penetration on a global scale. Smartphones are approaching full penetration in half that period. (For what it's worth, I note that tablet computers attained widespread usage in the developed world even faster than smartphones had.)

Already the general consensus among researchers, NGOs, economists, and business leaders holds that smartphones have changed the world for everyone.

It's easy to see why they all agree. In the late 1980s, a cell phone—of any kind, let alone a smartphone—remained a tremendous luxury. Today, poor farmers in Africa and India consider the smartphone a common tool by which to check market prices and communicate with buyers and shippers. This has introduced rich sources of information into their lives. Aside from calling distant relatives as they could on their earlier cell phones, they can now receive medical advice from distant doctors, check prices in neighboring villages before choosing a market, and send money to a friend. In Kenya, the M-Pesa network, using mobile phones, has effectively leapfrogged legacy banking systems and created a nearly frictionless transaction-and-payment system for millions of people formerly unable to participate in the economy except through barter.[8]

The prices of smartphones, following the curve of Moore's Law downward, have fallen so much that they are nearly ubiquitous in vibrant but still impoverished African capitals such as Lagos. Peter Diamandis observed, in his book *Abundance: The Future Is Better Than You Think,* that these devices provide Masai warriors in the bush with access to more information than the president of the United States had access to about two decades ago.[9] And we are early in this trend. Within five years, the prices of smartphones and tablet computers as powerful as the iPhones and iPads we use in the United States in 2017 will fall to less than $30, putting into the hands of all but the poorest of the poor the power of a connected supercomputer. By 2023, those smartphones will have more computing power than our own brains.* (That wasn't a typo—at the rate at which computers are advancing, the iPhone 11 or 12 will have greater computing power than our brains do.)

The acceleration in computation feeds on itself, ad infinitum. The availability of cheaper, faster chips makes faster computation available at a lower price, which enables better research tools and production technologies. And those, in turn, accelerate the process of computer development. But now Moore's Law applies, as we have described above, not just to smartphones and PCs but to everything. Change has always been the norm and the one constant; but we have never experienced change like this, at such

* This is not to say that smartphones will replace our brains. Semiconductors and existing software have thus far failed to pass a Turing Test (by tricking a human into thinking that a computer is a person), let alone provide broad-based capabilities that we expect all humans to master in language, logic, navigation, and simple problem solving. A robot can drive a car quite effectively, but thus far robots have failed to tackle tasks that would seem far simpler, such as folding a basket of laundry. The comprehension of the ever-changing jumble of surfaces that this task entails is something that the human brain does without even trying.

a pace, or on so many fronts: in energy sources' move to renewables; in health care's move to digital health records and designer drugs; in banking, in which a technology called the blockchain distributed ledger system threatens to antiquate financial systems' opaque procedures.*

It is noteworthy that, Moore's Law having turned fifty, we are reaching the limits of how much you can shrink a transistor. After all, nothing can be smaller than an atom. But Intel and IBM have both said that they can adhere to the Moore's Law targets for another five to ten years. So the silicon-based computer chips in our laptops will surely match the power of a human brain in the early 2020s, but Moore's Law may fizzle out after that.

What happens after Moore's Law? As Ray Kurzweil explains, Moore's law isn't the be-all and end-all of computing; the advances will continue regardless of what Intel and IBM can do with silicon. Moore's Law itself was just one of five paradigms in computing: electromechanical, relay, vacuum tube, discrete transistor, and integrated circuits. Technology has been advancing exponentially since the advent of evolution on Earth, and computing power has been rising exponentially: from the mechanical calculating devices used in the 1890 U.S. Census, via the machines that cracked the Nazi enigma code, the CBS vacuum-tube

* The blockchain is an almost incorruptible digital ledger that can be used to record practically anything that can be digitized: birth and death certificates, marriage licenses, deeds and titles of ownership, educational degrees, medical records, contracts, and votes. Bitcoin is one of its many implementations.

computer, the transistor-based machines used in the first space launches, and more recently the integrated circuit–based personal computer.

With exponentially advancing technologies, things move very slowly at first and then advance dramatically. Each new technology advances along an S-curve—an exponential beginning, flattening out as the technology reaches its limits. As one technology ends, the next paradigm takes over. That is what has been happening, and it is why there will be new computing paradigms after Moore's Law.

Already, there are significant advances on the horizon, such as the graphics-processor unit, which uses parallel computing to create massive increases in performance, not only for graphics, but also for neural networks, which constitute the architecture of the human brain. There are 3-D chips in development that can pack circuits in layers. IBM and the Defense Advanced Research Projects Agency are developing cognitive computing chips. New materials, such as gallium arsenide, carbon nanotubes, and graphene, are showing huge promise as replacements for silicon. And then there is the most interesting—and scary—technology of all: quantum computing.

Instead of encoding information as either a zero or a one, as today's computers do, quantum computers will use quantum bits, or qubits, whose states encode an entire range of possibilities by capitalizing on the quantum phenomena of superposition and entanglement. Computations that would take today's computers thousands of years, these will perform in minutes.

So the computer processors that fuel the technologies that are changing our lives are getting ever faster, smaller, and cheaper. There may be some temporary slowdowns as they first proceed along new S-curves, but the march of technology will continue. These technology advances already make me feel as if I am on a roller coaster. I feel the ups and downs as excitement and disappointment. Often, I am filled with fear. Yet the ride has only just started; the best—and the worst—is ahead.

Are we truly ready for this? And, more important, how can we better shape and control the forces of that world in ways that give us more agency and choice?