



The Fourth Industrial Revolution

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Foreword

We live in exciting times of fundamental technological change. The pace and scope of groundbreaking scientific and technological advances coming from research facilities, start-ups and large organizations never cease to amaze me. The “science fiction” of yesterday is today becoming a reality in new products and services that we won’t be able to imagine having lived without.

These rapid advances in technology, however, are doing more than providing us with new capabilities—they are changing the way we live, work and relate to one another. As Klaus Schwab describes in this timely and insightful book, the convergence of digital technologies with breakthroughs in materials science and biology means that we are seeing the emergence of entirely new ways in which to live. In both subtle and explicit ways, technology is also changing what it means to be human.

As the Founder and Executive Chairman of the World Economic Forum and its internationally renowned annual meeting in Davos, Switzerland, Klaus Schwab is uniquely placed to synthesize the experiences and views of leading global economic and technological experts, leaders of the world’s largest businesses and the perspectives of government and civil society representatives into panoramic view of the challenges ahead.

He points out that the three previous industrial revolutions all created major societal change and opportunity, but today’s transformation is unique in terms of the great speed with which new ideas and technologies are spreading around the world. Every company across every industry is now compelled to reconsider their traditional ways of doing business to

keep pace with rapidly changing technology and consumer expectations.

In the coming decades, the technologies driving the fourth industrial revolution will fundamentally transform the entire structure of the world economy, our communities and our human identities. These profound changes highlight the great responsibilities we face as a civilization. We have to make choices and contribute as citizens, government officials and business leaders to design systems that ensure benefits and risks are carefully weighed and new systems arise with common values and clear purposes in mind that benefit everyone on our planet. In all cases, particularly with artificial intelligence, genetic engineering and other technologies that could conceivably escape our control, we need to take care in building systems that minimize risks and improve the human condition.

The Fourth Industrial Revolution is an important book for understanding the major trends shaping our world. It provides a way of thinking and analyzing the historic changes taking place so that we can collectively create an empowering, prosperous, human-centered future for all. I am sure that you will gain valuable insights for navigating the future from reading this fascinating book.

—*Marc R. Benioff, Chairman and CEO, Salesforce, and a member of the World Economic Forum Board of Trustees*

Introduction

Of the many diverse and fascinating challenges we face today, the most intense and important is how to understand and shape the new technology revolution, which entails nothing less than a transformation of humankind. We are at the beginning of a revolution that is fundamentally changing the way we live, work, and relate to one another. In its scale, scope and complexity, what I consider to be the fourth industrial revolution is unlike anything humankind has experienced before.

We have yet to grasp fully the speed and breadth of this new revolution. Consider the unlimited possibilities of having billions of people connected by mobile devices, giving rise to unprecedented processing power, storage capabilities and knowledge access. Or think about the staggering confluence of emerging technology breakthroughs, covering wide-ranging fields such as artificial intelligence (AI), robotics, the internet of things (IoT), autonomous vehicles, 3D printing, nanotechnology, biotechnology, materials science, energy storage and quantum computing, to name a few. Many of these innovations are in their infancy, but they are already reaching an inflection point in their development as they build on and amplify each other in a fusion of technologies across the physical, digital and biological worlds.

We are witnessing profound shifts across all industries, marked by the emergence of new business models, the disruption¹ of incumbents and the reshaping of production, consumption, transportation and delivery systems. On the societal front, a paradigm shift is underway in how we work and communicate, as well as how we express, inform and entertain

ourselves. Equally, governments and institutions are being reshaped, as are systems of education, healthcare and transportation, among many others. New ways of using technology to change behavior and our systems of production and consumption also offer the potential for supporting the regeneration and preservation of natural environments, rather than creating hidden costs in the form of externalities.

The changes are historic in terms of their size, speed and scope.

While the profound uncertainty surrounding the development and adoption of emerging technologies means that we do not yet know how the transformations driven by this industrial revolution will unfold, their complexity and interconnectedness across sectors imply that all stakeholders of global society—governments, business, academia, and civil society—have a responsibility to work together to better understand the emerging trends.

Shared understanding is particularly critical if we are to shape a collective future that reflects common objectives and values. We must have a comprehensive and globally shared view of how technology is changing our lives and those of future generations, and how it is reshaping the economic, social, cultural and human context in which we live.

The changes are so profound that, from the perspective of human history, there has never been a time of greater promise or potential peril. My concern, however, is that decision makers are too often caught in traditional, linear (and nondisruptive) thinking or too absorbed by immediate concerns to think strategically about the forces of disruption and innovation shaping our future.

I am well aware that some academics and professionals consider the developments that I am looking at as simply a part of the third industrial revolution. Three reasons, however, underpin my conviction that a fourth and distinct revolution is under way:

Velocity: Contrary to the previous industrial revolutions, this one is evolving at an exponential rather than linear pace. This is the result of the multifaceted, deeply interconnected world we live in and the fact that new

technology begets newer and ever more capable technology.

Breadth and Depth: It builds on the digital revolution and combines multiple technologies that are leading to unprecedented paradigm shifts in the economy, business, society, and individually. It is not only changing the “what” and the “how” of doing things but also “who” we are.

Systems Impact: It involves the transformation of entire systems, across (and within) countries, companies, industries and society as a whole.

In writing this book, my intention is to provide a primer on the fourth industrial revolution—what it is, what it will bring, how it will impact us, and what can be done to harness it for the common good. This volume is intended for all those with an interest in our future who are committed to using the opportunities of this revolutionary change to make the world a better place.

I have three main goals:

- to increase awareness of the comprehensiveness and speed of the technological revolution and its multifaceted impact,
- to create a framework for thinking about the technological revolution that outlines the core issues and highlights possible responses, and
- to provide a platform from which to inspire public–private cooperation and partnerships on issues related to the technological revolution.

Above all, this book aims to emphasize the ways in which technology and society coexist. Technology is not an exogenous force over which we have no control. We are not constrained by a binary choice between “accept and live with it” and “reject and live without it.” Instead, take dramatic technological change as an invitation to reflect about who we are and how we see the world. The more we think about how to harness the technology revolution, the more we will examine ourselves and the underlying social models that these technologies embody and enable, and the more we will have an opportunity to shape the revolution in a manner that improves the state of the world.

Shaping the fourth industrial revolution to ensure that it is empowering and human-centered, rather than divisive and dehumanizing, is not a task for any single stakeholder or sector or for any one region, industry or culture. The fundamental and global nature of this revolution means it will affect and be influenced by all countries, economies, sectors and people. It is, therefore, critical that we invest attention and energy in multistakeholder cooperation across academic, social, political, national and industry boundaries. These interactions and collaborations are needed to create positive, common and hope-filled narratives, enabling individuals and groups from all parts of the world to participate in, and benefit from, the ongoing transformations.

Much of the information and my own analysis in this book are based on ongoing projects and initiatives of the World Economic Forum and have been developed, discussed and challenged at recent Forum gatherings. Thus, this book also provides a framework for shaping the future activities of the World Economic Forum. I have also drawn from numerous conversations I have had with business, government and civil society leaders, as well as technology pioneers and young people. It is, in that sense, a crowd-sourced book, the product of the collective enlightened wisdom of the Forum's communities.

This book is organized in three chapters. The first is an overview of the fourth industrial revolution. The second presents the main transformative technologies. The third provides a deep dive into the impact of the revolution and some of the policy challenges it poses. I conclude by suggesting practical ideas and solutions on how best to adapt, shape and harness the potential of this great transformation.

1. The Fourth Industrial Revolution

1.1 Historical Context

The word “revolution” denotes abrupt and radical change. Revolutions have occurred throughout history when new technologies and novel ways of perceiving the world trigger a profound change in economic systems and social structures. Given that history is used as a frame of reference, the abruptness of these changes may take years to unfold.

The first profound shift in our way of living—the transition from foraging to farming—happened around 10,000 years ago and was made possible by the domestication of animals. The agrarian revolution combined the efforts of animals with those of humans for the purpose of production, transportation and communication. Little by little, food production improved, spurring population growth and enabling larger human settlements. This eventually led to urbanization and the rise of cities.

The agrarian revolution was followed by a series of industrial revolutions that began in the second half of the 18th century. These marked the transition from muscle power to mechanical power, evolving to where today, with the fourth industrial revolution, enhanced cognitive power is augmenting human production.

The first industrial revolution spanned from about 1760 to around 1840. Triggered by the construction of railroads and the invention of the steam engine, it ushered in mechanical production. The second industrial

revolution, which started in the late 19th century and into the early 20th century, made mass production possible, fostered by the advent of electricity and the assembly line. The third industrial revolution began in the 1960s. It is usually called the computer or digital revolution because it was catalyzed by the development of semiconductors, mainframe computing (1960s), personal computing (1970s and '80s) and the internet (1990s).

Mindful of the various definitions and academic arguments used to describe the first three industrial revolutions, I believe that today we are at the beginning of a fourth industrial revolution. It began at the turn of this century and builds on the digital revolution. It is characterized by a much more ubiquitous and mobile internet, by smaller and more powerful sensors that have become cheaper, and by artificial intelligence and machine learning.

Digital technologies that have computer hardware, software and networks at their core are not new, but in a break with the third industrial revolution, they are becoming more sophisticated and integrated and are, as a result, transforming societies and the global economy. This is the reason why Massachusetts Institute of Technology (MIT) professors Erik Brynjolfsson and Andrew McAfee have famously referred to this period as “the second machine age,”² the title of their 2014 book, stating that the world is at an inflection point where the effect of these digital technologies will manifest with “full force” through automation and the making of “unprecedented things.”

In Germany, there are discussions about “Industry 4.0,” a term coined at the Hannover Fair in 2011 to describe how this will revolutionize the organization of global value chains. By enabling “smart factories,” the fourth industrial revolution creates a world in which virtual and physical systems of manufacturing globally cooperate with each other in a flexible way. This enables the absolute customization of products and the creation of new operating models.

The fourth industrial revolution, however, is not only about smart and connected machines and systems. Its scope is much wider. Occurring simultaneously are waves of further breakthroughs in areas ranging from

gene sequencing to nanotechnology, from renewables to quantum computing. It is the fusion of these technologies and their interaction across the physical, digital and biological domains that make the fourth industrial revolution fundamentally different from previous revolutions.

In this revolution, emerging technologies and broad-based innovation are diffusing much faster and more widely than in previous ones, which continue to unfold in some parts of the world. This second industrial revolution has yet to be fully experienced by 17% of world, as nearly 1.3 billion people still lack access to electricity. This is also true for the third industrial revolution, with more than half of the world's population, 4 billion people, most of whom live in the developing world, lacking internet access. The spindle (the hallmark of the first industrial revolution) took almost 120 years to spread outside of Europe. By contrast, the internet permeated across the globe in less than a decade.

Still valid today is the lesson from the first industrial revolution—that the extent to which society embraces technological innovation is a major determinant of progress. The government and public institutions, as well as the private sector, need to do their part, but it is also essential that citizens see the long-term benefits.

I am convinced that the fourth industrial revolution will be every bit as powerful, impactful and historically important as the previous three. However, I have two primary concerns about factors that may limit the potential of the fourth industrial revolution to be effectively and cohesively realized.

First, I feel that the required levels of leadership and understanding of the changes under way, across all sectors, are low when contrasted with the need to rethink our economic, social and political systems to respond to the fourth industrial revolution. As a result, both at the national and global levels, the requisite institutional framework to govern the diffusion of innovation and mitigate the disruption is inadequate at best and, at worst, absent altogether.

Second, the world lacks a consistent, positive and common narrative that outlines the opportunities and challenges of the fourth industrial

revolution, a narrative that is essential if we are to empower a diverse set of individuals and communities and avoid a popular backlash against the fundamental changes under way.

1.2 Profound and Systemic Change

The premise of this book is that technology and digitization will revolutionize everything, making the overused and often ill-used adage “this time is different” apt. Simply put, major technological innovations are on the brink of fueling momentous change throughout the world—inevitably so.

The scale and scope of change explain why disruption and innovation feel so acute today. The speed of innovation in terms of both its development and diffusion is faster than ever. Today’s disruptors (Airbnb, Uber, Alibaba and the like—now household names) were relatively unknown just a few years ago. The ubiquitous iPhone was first launched in 2007. Yet there will be as many as 2 billion smartphones by the end of 2015. In 2010 Google announced its first fully autonomous car. Such vehicles could soon become a widespread reality on the road.

One could go on. But it is not only speed; returns to scale are equally staggering. Digitization means automation, which in turn means that companies do not incur diminishing returns to scale (or less of them, at least). To give a sense of what this means at the aggregate level, compare Detroit in 1990 (then a major center of traditional industries) with Silicon Valley in 2014. In 1990, the three biggest companies in Detroit had a combined market capitalization of \$36 billion, revenues of \$250 billion, and 1.2 million employees. In 2014, the three biggest companies in Silicon Valley had a considerably higher market capitalization (\$1.09 trillion), generated roughly the same revenues (\$247 billion), but with about 10 times fewer employees (137,000).³

The fact that a unit of wealth is created today with much fewer workers compared with 10 or 15 years ago is possible because digital businesses have marginal costs that tend towards zero. Additionally, the reality of

the digital age is that many new businesses provide “information goods” with storage, transportation and replication costs that are virtually nil. Some disruptive tech companies seem to require little capital to prosper. Businesses such as Instagram or WhatsApp, for example, did not require much funding to start up, changing the role of capital and scaling business in the context of the fourth industrial revolution. Overall, this shows how returns to scale further encourage scale and influence change across entire systems.

Aside from speed and breadth, the fourth industrial revolution is unique because of the growing harmonization and integration of so many different disciplines and discoveries. Tangible innovations that result from interdependencies among different technologies are no longer science fiction. Today, for example, digital fabrication technologies can interact with the biological world. Some designers and architects are already mixing computational design, additive manufacturing, materials engineering and synthetic biology to pioneer systems that involve the interaction among micro-organisms, our bodies, the products we consume, and even the buildings we inhabit. In doing so, they are making (and even “growing”) objects that are continuously mutable and adaptable (hallmarks of the plant and animal kingdoms).⁴

In *The Second Machine Age*, Brynjolfsson and McAfee argue that computers are so dexterous that it is virtually impossible to predict what applications they may be used for in just a few years. Artificial intelligence (AI) is all around us, from self-driving cars and drones to virtual assistants and translation software. This is transforming our lives. AI has made impressive progress, driven by exponential increases in computing power and by the availability of vast amounts of data, from software used to discover new drugs to algorithms that predict our cultural interests. Many of these algorithms learn from the “bread crumb” trails of data that we leave in the digital world. This results in new types of “machine learning” and automated discovery that enable “intelligent” robots and computers to self-program and find optimal solutions from first principles.

Applications such as Apple’s Siri provide a glimpse of the power of one

subset of the rapidly advancing AI field—so-called intelligent assistants. Only two years ago, intelligent personal assistants were starting to emerge. Today, voice recognition and artificial intelligence are progressing so quickly that talking to computers will soon become the norm, creating what some technologists call ambient computing, in which robotic personal assistants are constantly available to take notes and respond to user queries. Our devices will become an increasing part of our personal ecosystem, listening to us, anticipating our needs, and helping us when required—even if not asked.

Inequality as a systemic challenge

The fourth industrial revolution will generate great benefits and big challenges in equal measure. A particular concern is exacerbated inequality. The challenges posed by rising inequality are hard to quantify as a great majority of us are consumers and producers, so innovation and disruption will both positively and negatively affect our living standards and welfare.

The consumer seems to be gaining the most. The fourth industrial revolution has made possible new products and services that increase at virtually no cost the efficiency of our personal lives as consumers. Ordering a cab, finding a flight, buying a product, making a payment, listening to music or watching a film—any of these tasks can now be done remotely. The benefits of technology for all of us who consume are incontrovertible. The internet, the smartphone and the thousands of apps are making our lives easier, and—on the whole—more productive. A simple device such as a tablet, which we use for reading, browsing and communicating, possesses the equivalent processing power of 5,000 desktop computers from 30 years ago, while the cost of storing information is approaching zero (storing 1GB costs an average of less than \$0.03 a year today, compared with more than \$10,000, 20 years ago).

The challenges created by the fourth industrial revolution appear to be mostly on the supply side—in the world of work and production. Over the past few years, an overwhelming majority of the most developed

countries and also some fast-growing economies such as China have experienced a significant decline in the share of labor as a percentage of GDP. Half of this drop is due to the fall in the relative price of investment goods,⁵ itself driven by the progress of innovation (which compels companies to substitute labor for capital).

As a result, the great beneficiaries of the fourth industrial revolution are the providers of intellectual or physical capital—the innovators, the investors, and the shareholders, which explains the rising gap in wealth between those who depend on their labor and those who own capital. It also accounts for the disillusionment among so many workers, convinced that their real income may not increase over their lifetime and that their children may not have a better life than theirs.

Rising inequality and growing concerns about unfairness present such a significant challenge that I will devote a section to this in [Chapter Three](#). The concentration of benefits and value in just a small percentage of people is also exacerbated by the so-called platform effect, in which digitally driven organizations create networks that match buyers and sellers of a wide variety of products and services and thereby enjoy increasing returns to scale.

The consequence of the platform effect is a concentration of few but powerful platforms that dominate their markets. The benefits are obvious, particularly to consumers: higher value, more convenience and lower costs. Yet so too are the societal risks. To prevent the concentration of value and power in just a few hands, we have to find ways to balance the benefits and risks of digital platforms (including industry platforms) by ensuring openness and opportunities for collaborative innovation.

These are all fundamental changes affecting our economic, social and political systems that are difficult to undo, even if the process of globalization itself were to somehow be reversed. The question for all industries and companies, without exception, is no longer “Am I going to be disrupted?” but “When is disruption coming, what form will it take and how will it affect me and my organization?”

The reality of disruption and the inevitability of the impact it will have on

us does not mean that we are powerless in the face of it. It is our responsibility to ensure that we establish a set of common values to drive policy choices and to enact the changes that will make the fourth industrial revolution an opportunity for all.

2. Drivers

Countless organizations have produced lists ranking the various technologies that will drive the fourth industrial revolution. The scientific breakthroughs and the new technologies they generate seem limitless, unfolding on so many different fronts and in so many different places. My selection of the key technologies to watch is based on research done by the World Economic Forum and the work of several of the Forum's Global Agenda Councils.

2.1 Megatrends

All new developments and technologies have one key feature in common: they leverage the pervasive power of digitization and information technology. All of the innovations described in this chapter are made possible and are enhanced through digital power. Gene sequencing, for example, could not happen without progress in computing power and data analytics. Similarly, advanced robots would not exist without artificial intelligence, which itself largely depends on computing power.

To identify the megatrends and convey the broad landscape of technological drivers of the fourth industrial revolution, I have organized the list into three clusters: physical, digital and biological. All three are deeply interrelated and the various technologies benefit from one another based on the discoveries and progress each makes.

2.1.1 Physical