ONE

Breakthroughs

Why We Need Them for Sustainable Development

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Imagine a world in which a daily home coronavirus test is as common and easy as brushing your teeth. A world in which, while on a lunch break, you can look at your phone to check on the real-time wanderings of a family of giraffes in the African savannah. Sitting on a bench outside your office, you take a refreshingly clean and deep breath, proud that your city's cloud computing system has enabled a stark decline in local particulate emissions, curtailing the asthma that affected you so much as a child. You dip into your digital wallet to send money to the mother giraffe's own virtual bank account, excited because you know the resources will support local conservation efforts targeted directly at the mother's preferences, as revealed through the local artificial intelligence (AI)–backed animal tracking systems.

For dinner, you order a delicious plant-based hamburger, one of many varieties that took over the fast-food market once traditional beef became too expensive—due partly to the cattle farmers who kept illegally expanding into tropical forests until eye-in-the-sky technology made the costs of doing so prohibitive. The burger ingredients happen to include rice grown by an enterprising farmer in Borno, the northeastern-most state in Nigeria. She recently started using low-cost solar panels to power her farm's irrigation pumps, paired with digitally verified high-yield seeds—ending a long battle against counterfeits—and some fertilizer-replacing microbes she used to increase the organic nutrients in her soil. All of this helped her annual crop output jump tenfold over the past few years. The huge productivity boost enabled her to start exporting to global markets through a new online agribusiness aggregator platform that provides all the services and technical assistance she needs to reach customers anywhere in the world.

Unbeknown to you as you chomp on your juicy burger, the rice farmer is only still in business thanks to the United Nations' AI-based disaster preparedness system. The previous year, the UN had worked with Agrotrack, Nigeria's trusted local multi-stakeholder data connector, to send the farmer an emergency text message, giving her a seventy-two-hour warning of the flood coming to her village. This allowed her to safeguard her farm equipment. Thanks to the national digital ID platform and integrated financial system, the farmer's family received an anticipatory digital cash transfer to buy emergency supplies prior to the flood. Borno's local safety net program had been set up in record time thanks to its open-source software and a design-for-scale approach.

This scenario may seem far-fetched but, technology-wise, it is not far off. In fact, all the relevant technologies either already exist or are likely to come to fruition very soon. If their cost is cheap enough and their design is good enough, each has the possibility for widespread global adoption. That is the view of the extraordinary range of authors contributing to this volume focused on breakthrough technologies relevant to the Sustainable Development Goals (SDGs)—the world's economic, social, and environmental objectives adopted by all countries in 2015, aiming at a 2030 horizon.

Why focus on technology amid a time of so much global economic, social, and environmental strain? Many readers might think, with good reason, that the world's foremost problems hinge on better policies and politics rather than science and technology. This would only be partly correct. There is no question that, in most societies, there is ample space for improving policies and politics. But there is also no question that, in most societies, better technology needs to play a crucial role in smoothing the path toward better sustainable development outcomes.

In a previous volume, focused on the SDG mantra of "Leave No One Behind,"[1] we outlined the world's overall trends relating to human deprivation. The overview of that book described the results of a careful country-by-country assessment of trends. It warned that the gap between business-as-usual trajectories and SDG achievement added up to roughly 44 million lives at stake by 2030, nearly 500 million people at risk of being left in extreme poverty in the same year, around 570 million people left without access to electricity, and nearly 2 billion people left behind on basic issues like access to sanitation. Meanwhile, in Sub-Saharan Africa, the region with the most extensive extreme poverty, agricultural

1. Kharas, McArthur, Ohno.

yields still lag far behind other regions,[2] despite framing a critical path to long-term poverty reduction.[3, 4] These are all issues on which gradualist approaches to progress simply will not achieve the SDG objectives. Breakthroughs are needed, in scientific underpinnings, in development of new products, and in supporting institutional systems.

More recently, COVID-19 has already contributed to at least 5 million premature deaths since early 2020, if not multiples more.[5] The pandemic has curtailed or reversed SDG progress in many parts of the world. It has placed additional strain on the basic tenets of international cooperation, which were already under widespread duress. By one estimate, the pandemic pushed an extra 100 million people into extreme poverty, wiping out all the gains since 2015, although hopefully some of the affected households will recover rapidly.[6] It has exacerbated inequalities within countries, as the most skilled and wealthy people benefited from soaring equity markets. It has heightened disparities between countries, as a handful of advanced economies quickly deployed economic stimuli and then vaccines at a breathtaking pace, while lower-income countries wait at the back of the line for their chance to do the same.

On the environmental side, recent evidence has also underscored the need for global breakthroughs. Despite a sharp drop-off in greenhouse gas emissions during the initial economic shutdowns, the International Energy Agency reports that global carbon dioxide emissions bounced back by December 2020 to be 2 percent higher than during the same month in 2019.[7] An August 2021 scientific report of the Intergovernmental Panel on Climate Change underscored the high current likelihood of at least a 1.5-degree Celsius increase in average global temperatures over the next two decades, accompanied by widespread increases in extreme weather events.[8] Absent imminent widespread transformations in the world's energy systems, many societies will be grappling with sharply intensified climate-related burdens in the pursuit of sustainable development.

Notwithstanding all the bad news, science and technology have offered some of the brightest sources of hope throughout the pandemic. Most prominently, multiple vaccines have been developed at unprecedented speeds, including highly efficacious versions deploying recent scientific breakthroughs in the use of messenger RNA (mRNA). The first approved vaccines were rolled out at the end of

2. Jayne and Sanchez.
3. Christiaensen and Martin.
4. McArthur and McCord.
5. *The Economist*; Anand and others.
6. Kharas and Dooley.
7. IEA (2021).
8. IPCC.

2020, and within nine months, more than 3 billion people around the world received at least one dose—far short of adequate for the modern world's needs, but extraordinarily rapid by any historical standard.

In other sectors, many economies have taken advantage of new digital payments technologies to provide rapid and hyper-targeted emergency support for people affected by the pandemic. The Bahamas, for example, introduced the world's first Central Bank virtual currency to improve access to finance across hundreds of islands. Sri Lanka overcame two decades of coordination challenges to introduce an electronic platform for its twice-weekly wholesale tea auction at the Ceylon Chamber of Commerce.[9] In Togo, the government leveraged its pioneering digital payments platform to partner with mobile providers, external nonprofits, and academics on AI-based algorithms that identify people most likely to need immediate support. The result was rapid-response social protection for citizens who would have previously only been identified through much more expensive, labor-intensive, and time-demanding survey methods.

New thresholds have been met in the energy industry, too. As of mid-2021, the cost of wind and solar energy generation has decreased enough for it to be the lowest new source of power for two-thirds of the global population.[10] For health, energy, agriculture, and many other technologies, the underlying forces of scientific and technological progress are offering unprecedented opportunities for change, if the world can align its economic and policy systems to take advantage of them. In December 2020, blogger Noah Smith quipped that "cheap taxis and fancy smoothies are out. Big Science is in."[11] In early 2021, *MIT Technology Review* went so far as to ask, "Are you ready to be a techno-optimist again?"[12]

Technology—the Bigger Picture

It is worth taking a moment to reflect on the broader role of technology in overall societal progress. Economists tend to track the evolution of societal technology through the indicator of "total factor productivity." In accounting terms, this is the residual contribution to aggregate economic output once all the inputs such as workers' labor, machines, and other forms of physical capital have been taken into account. Macroeconomic data suggest that the rate of total factor productivity growth in the world has declined since 1972, despite the many advances since that time, but the pandemic may reverse this trend.

9. Dorst.
10. Eckhouse.
11. Smith.
12. Rotman.

Consider major technology transitions in years past, like the shift from mainframes to personal computers, and now to the cloud and AI.[13] Some analysts predict new innovations over the coming decade could be even more consequential. Others are skeptical about the geographic coverage of new innovations, noting the complexities of encouraging technological uptake in lower-income countries—or technological diffusion, in economics jargon. For example, it is now more than 140 years since Thomas Edison lit the first light bulb in Menlo Park, New Jersey. Yet, as of 2019, there were still 770 million people in developing countries lacking access to modern electricity.[14] With this track record, will new breakthrough technologies be primarily for the world's wealthier consumers? Or is it conceivable that the poorest individuals on our planet, those who are a top priority for the SDGs, could share in the benefits by 2030 as well?

Some analysts argue that traditional metrics can underestimate the widespread impacts of technology. For example, it is widely understood that consumer satisfaction does not always track gross domestic product (GDP), so deriving the impact of technological innovation from its effect on GDP—which is itself notoriously imprecise in capturing measures of quality or new products—could be highly misleading. Research by Erik Brynjolfsson and colleagues suggests that technology has actually led to far more rapid growth in consumer welfare via the addition of new goods (like Facebook) and free goods (like WhatsApp long-distance phone calls or smartphone cameras) than is captured by measured GDP growth.[15]

More recent research draws attention to the varying rates of progress across different types of technology. A notable 2021 study by Anuraag Singh and colleagues examines multi-decade rates of improvement across 1,757 technology domains within the United States.[16] They estimate that more than two-thirds of the domains are improving by less than 15 percent per year, with the slowest rates registered for relatively simple mechanisms like automatic vehicle washing and handheld tools for cutting, scraping, and drilling. At the other end of the spectrum, slightly more than 10 percent of technology domains are improving by more than 36 percent per year, with a handful of domains related to software, the internet, and enterprise network management improving the fastest, sometimes by more than 200 percent per year.

Within the broader context of global sustainable development, governments recognized the multi-dimensional challenge of measuring progress when they

13. Gordon (2014).
14. IEA (2020).
15. Brynjolfsson and others.
16. Singh, Triulzi, and Magee.

agreed to seventeen SDGs in 2015. Sustainable development cannot be collapsed into a single metric. Nor has any country yet succeeded in fostering adequate progress across the interconnected economic, social, and environmental challenges of sustainable development to declare overall societal success.[17] Issues of equity, agency, natural resource protection, and well-being must all be taken into account. The contribution of technology to the SDGs, then, must go beyond its direct contribution to growth or any specific SDG outcomes and incorporate the indirect effects it will have on the 5 Ps of the SDGs—People, Planet, Prosperity, Peace, and Partnerships.

Crucially, the uptake of technology depends on both the market demand for new products and, usually, a decline in price. Many of the technologies described in this book follow Wright's Law: a steady drop in price linked to the cumulative production of a given product. Put forward by an aeronautical engineer, T. P. Wright, in 1936 to estimate the decline in cost for airplanes,[18] Wright's Law has since been found to apply to many, if not most, new technologies. Its importance derives from two considerations: existing technologies have an in-built cost advantage because they already have years of accumulated production under their belt; but new technologies that appear to be far too expensive to be of use when first introduced can see very rapid price declines in a short period of time. As an example, consider the case of photos: 85 billion photos were taken in 2000 compared to 25 billion in 1980. But by 2021, that number has leapt ahead—an estimated 1.4 trillion photos will be taken. This is the power of readily available technology coupled with low (or zero) prices.

This leads to another powerful insight, known as Amara's Law, which states that people tend to overestimate what can be achieved in a year but underestimate what can be achieved in a decade. This is due to the potential exponential nature of progress, which can lead to nonlinear change in the adoption of a specific technology and unprecedented opportunities in complementary technologies. Consider, for example, the introduction of the iPhone in 2007. Its "app store" established a new framework for mobile technology that allowed huge numbers of people from around the world to develop countless apps, for a seemingly infinite array of purposes, spanning everything from communications to entertainment, astronomy, horticulture, physical fitness, mental health, and even digital vaccine passports.

In the most profound cases, the systematic diffusion of new technologies can amount to a matter of life and death. Antiretroviral therapy (ART) for HIV/AIDS treatment frames a poignant example of this over recent decades, deeply

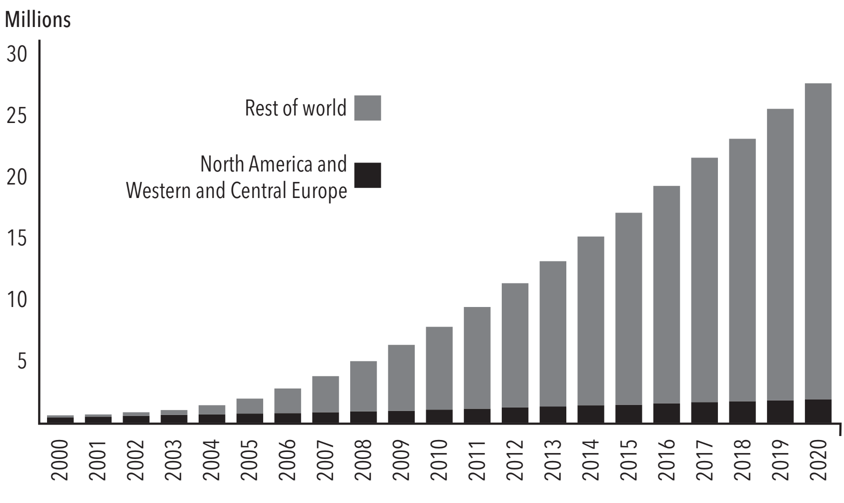
17. Kharas and McArthur.
18. Wright.

interwoven with the successes of the Millennium Development Goals (MDGs), the anti-poverty predecessors to the SDGs. It was only in 1996 that ART's breakthrough results in translating HIV/AIDS from a death sentence to a treatable disease were presented publicly.[19] But as of the early 2000s, when the vast majority of people infected by the virus lived in low-income Sub-Saharan African countries, the technology was not accessible due to its price and a lack of global systems to deliver medication to those most in need.

Over the subsequent two decades, a combination of new donor-funded institutions like the Global Fund to Fight AIDS, Tuberculosis, and Malaria and the U.S. Presidential Emergency Program for AIDS Relief combined with pioneering local leaders and pooled purchasing agreements to drive costs down. The result, coupled with evolving health protocols developed through evidence-based academic debates in top health journals, plus a fastidious international policy focus on tracking service delivery targets through scaled-up health systems in lower-income geographies, is more than 27 million people now receiving lifesaving ART, as shown in figure 1-1. Today, the vast majority of people receiving treatment live in low- and middle-income countries. A mix of science, products, and business and delivery systems combined to generate the global breakthrough.

A separately complex array of factors is presently playing out in global energy

Figure 1-1. Antiretroviral Therapy Coverage, 2000–2020



Source: UNAIDS 2021 estimates

19. Forsythe and others.

markets that will drive much of the world's path on climate change. Unlike the ART example above, emissions-reducing energy sources like solar and wind power are competing against existing sources like coal and other fossil fuels, which are typically brought to market through expensive infrastructure systems built to last for decades. To "win" the competition against older technologies, new energy technologies ultimately need to be cheaper per unit of energy produced and consumed, in order for incentives to align around widespread adoption. Until recently, the low-carbon technologies have not been adequately low-cost, and the rate of progress in reducing cost has not been fast enough to displace high-carbon technologies.

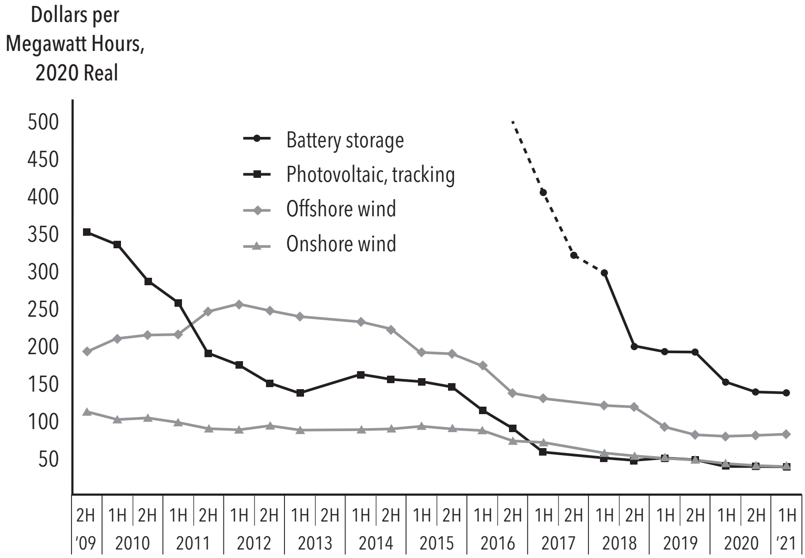
A blend of policy subsidies, market incentives, and expanded productive capacity helped drop the price of photovoltaic solar energy by roughly 90 percent between 2010 and 2020, as shown in figure 1-2. According to Bloomberg, solar power now offers the world's lowest levelized cost of energy.[20] In parallel, energy storage has long been an ambition for capturing any breakthroughs in renewable generation, so the 89 percent decline in lithium-ion battery costs over the same period marks a powerful complementary development. The concurrent pricing breakthroughs offer great potential for economies that can mobilize adequate capital to take advantage, which shifts attention toward government spending and systemic policy incentives.

A Remarkable Range of Insights

With these broader trends in mind, and against the backdrop of COVID-19 and the deepest, widest peacetime recession in history, we asked a dozen remarkable authors from science, business, civil society, and policy worlds to reflect on the impact that technology could have on the human condition in the next ten years. Our challenge to the authors was simple: given the current state of technology and technological progress within your domain of expertise, what is a vision of success? What are the key ingredients needed for a nonlinear breakthrough to be achieved? And what are the priority actions for implementation? Our experts tackled these questions under three parameters. First, we asked them to focus on what could reasonably happen by the SDG deadline of 2030. This meant that technologies had to be reasonably mature, given the nature of diffusion and impact—no futuristic quantum computing or nuclear fusion. Second, we asked them to focus on issues directly pertinent to SDG-relevant outcomes, whether economic, social, or environmental—not the future of gaming or entertainment. Third, we asked authors to focus on technologies that will affect outcomes at

20. Eckhouse.

Figure 1-2. Global Levelized Cost of Energy Benchmarks, 2009–2021



Source: BloombergNEF (2021)

The global benchmark is a country-weighted average using the latest annual capacity additions. The storage levelized cost of energy (LCOE) is reflective of a utility-scale Li-ion battery storage system with four-hour duration running at a daily cycle and includes charging costs assumed to be 60 percent of the wholesale average power price. All LCOEs calculations are unsubsidized. In 2H 2017, BNEF did not publish any update. The dashed line with the circle markers reflects derived LCOEs based on historic batter pack prices, while the continuous line reflects collected project data from 2018. For hydrogen-fired power and coal- and gas-fired power with carbon capture and storage (CCS), the global LCOE benchmark is a simple country average including China, Europe, the U.S., Japan, and India.

a substantial scale, such as hundreds of millions of people or substantial geographic coverage—no private space travel or flying cars.

Each of our experts responded with stories that reflect big dreams and ambitions for what the future may bring. These are not projections or forecasts as to what will happen—merely reasoned and reasonable conjectures about what *could* happen. The topics covered are not exhaustive. There are dozens if not hundreds of other technologies that could have been included. We do not claim that the topics that have been chosen are *the* most important breakthroughs—unlike, say, the inspiring annual top ten breakthrough technologies compiled by the *MIT Technology Review*.[21] Our intent is to provide a glimpse into the possibilities for the future of sustainable development.

21. *MIT Technology Review*.

A Pragmatic Approach

People are often classified as techno-optimists or techno-pessimists.[22] Like any pendulum of public debate, most of the time is spent at the ends of each swing, with one or the other group being in the ascendancy. We prefer to describe ourselves and our chapter authors as techno-realists—aware of both the essential role of technological advance and mindful of the many risks that new solutions can bring. Admittedly, we did ask all of the authors to consider risks, but we did not seek here to harp on them. This volume aims to draw attention to ways in which nonlinearities in technology can drive progress. As a blanket caveat, we can only underscore the frequency with which positive technological breakthroughs are accompanied by unexpected downsides. These always require careful monitoring and response, especially from policymakers who are mandated with protecting public well-being.

In this book, our pragmatic approach to technology is segmented into three parts, focused on (1) underlying scientific advances, (2) the evolution of applications, and (3) supportive systems. When all three are progressing at the same time, technologies see huge advances in their potential to drive progress at scale.

Scientific Advance

Consider first the question of whether the rate of scientific progress, what the economist Tyler Cowen terms the "science of science," is accelerating.[23] Cowen and coauthor Ben Southwood summarize their findings by noting that the growth rate of high-quality patents is slowing, that crop yields are no longer rising as rapidly as before, that Moore's Law is decelerating, and that life expectancy is flattening. True, the number of scientists and the resources devoted to research and development are growing, but those are inputs into the scientific process rather than outcomes. Nicholas Bloom and others have estimated that research productivity—the contribution of research to economic growth per unit of research input—has declined by more than 5 percent per year in the United States over the last ninety years—implying that research today is only 1 percent as productive as it was ninety years ago.[24]

Most metrics of scientific progress consider whether existing production of goods and services is being done in a faster, cheaper, or more efficient way. It is

22. Among the most renowned pessimists are the economists Robert Gordon and Tyler Cowen, and venture capitalist Peter Thiel. Among the most renowned optimists are economists Erik Brynjolffson and Joel Mokyr, and the billionaire entrepreneur Elon Musk.

23. Cowen and Southwood.

24. Bloom and others.

far harder to measure and understand the contributions of science to new products or different quality products. William Nordhaus examines related questions for a single product, the price of light.[25] He finds that the true price of light has been falling far faster than what is shown by traditional price indices, so that the "volume" of quality-adjusted light consumed is much higher than officially measured. This is important for understanding how much scientific progress in light (most recently, the advent of LED bulbs) has contributed to real consumer welfare.

Another feature of Nordhaus's work is of relevance to this book. In his long historical study, dating back to 1800 (with some conjectures for pre-Neolithic times), Nordhaus shows that technological advances are not linear but display step functions. In his example, the price of light was stagnant for twenty years between 1970 and 1990, before collapsing to one-fifth of its level in 1992 with the introduction of compact fluorescent bulbs.

It is these step changes that the first four chapters in this book seek to capture.

The introduction of the mRNA vaccines to combat COVID-19 is one of the major successes of our times. The biomedical advances that made it possible are very recent. The early detection of the virus was made possible through genome sequencing; Fred Sanger sequenced the first virus in 1977, but the speed of sequencing and reduction in costs only took giant steps forward in 2007, when a new technique combining gene chip technology with modern gene sequencing machines replaced the relatively more cumbersome, expensive, and slower polymerase chain reaction technology.[26] Pardis Sabeti, one of our contributors, rapidly generated and made public genetic sequence data on the Ebola virus in the middle of the major 2014 outbreak in West Africa, a seminal contribution that helped inform medical and policy responses. Several years later, similar technologies enabled the SARS-CoV-2 virus to be sequenced by Chinese researchers just ten days after a rapid response team was dispatched by the China Center for Disease Control to Wuhan. Today, new technology already is advancing to produce monoclonal antibodies to defend against potential future epidemics.

In chapter 2 of this volume, Yolanda Botto-Lodovico and Pardis Sabeti suggest that we should celebrate the new medical technologies for their life-saving potential. But they are even more ambitious in their vision about the impact of biological advances. When combined with new information systems that permit real-time viral surveillance, they envisage a world where the ravages of epidemics and pandemics can be dramatically reduced. The impact would be extraordinary. The costs of COVID-19 are still being tallied, but the economic losses

25. Nordhaus.
26. Shendure and others.

alone amount to US$10 trillion dollars, according to the Global Preparedness Monitoring Board.[27] What is more, the rapid spread of infectious disease is not a rarity; SARS, Ebola, MERS, Zika, and Nipah outbreaks preceded COVID-19 in this century. If pandemic preparedness can be built so as to mitigate the impact of future infectious disease, the benefits to the world, and to the poorest populations, could be highly significant. Botto-Lodovico and Sabeti show how this could be done through global cooperation to use the many advances of biomedical science and information technology. Pandemic preparedness everywhere would be a major breakthrough in global sustainable development.

In chapter 3, Zachary Bogue focuses on how new food and agricultural technologies can contribute to sustainability and planetary health. He describes the world as moving from the petroleum century to the microbe century. The Haber-Bosch process, sometimes dubbed the most important invention of the twentieth century,[28] poses a wicked problem. It creates synthetic nitrogen fertilizers that have allowed billions of people to live prosperous lives, but its production requires large amounts of energy, typically from fossil fuels, which is disastrous for climate change. Fertilizer's distribution contributes to nitrification and dead zones in oceans and lakes, which is disastrous for biodiversity. Simply put, it is an unsustainable technology that must be replaced. Bogue gives examples of companies already using microbial manufacturing to deliver nitrogen to plants and to make new kinds of environmentally friendly pesticides. He offers other examples of how science is reducing carbon emissions associated with farming: adding kelp to animal feed can reduce methane emissions by up to 99 percent; leather can be replaced with fabrics made from mycelium, found in mushrooms. Use of these technologies can permit sustainable, healthy nutrition for billions of people without recourse to the nitrogen fertilizers of Haber-Bosch.

A third example of a step-change scientific advance is the extraordinary fall in the price of solar power. As Vijay Modi shows in chapter 4, utility scale solar power has become nearly free, with some contracts as low as 1.5 cents per kilowatt hour (kWh). This is only one-tenth the price that the International Energy Agency forecasted for 2020 back in 2010,[29] and it can be compared to typical household solar systems often being implemented in much of Africa at costs of around 100 cents per kWh, when storage also needs to be included. The age of unlimited cheap power could be descending on us. Modi's chapter describes how such technologies can now be leveraged to benefit smallholder farmers. He points out that most of the cost of solar home systems today is actually for battery storage

27. Global Preparedness Monitoring Board.
28. Kuijpers.
29. IEA (2010).

and for metering, rather than for the electric power itself. Modi shows how these costs can be reduced dramatically if consumers shift their power demand to the daytime, when solar is readily available, instead of to evening hours. Almost-free power, at least at midday, could revolutionize the lives of millions of smallholder farmers who currently lack access to national electric grids, and to the lives of the women and girls in their households who are forced to collect fuel-wood and inhale particulates from dirty, open-fire combustion.

Ecosystem science is also expanding. In chapter 5, Jonathan Ledgard proposes "interspecies money" as a way of revolutionizing how conservation is practiced. He points out that the 2020s will be the most consequential decade for nonhuman life in recorded history. Furthermore, because the richest areas of biodiversity are in the tropics, poor people—the 1.6 billion living in fragile ecosystems—will be the principal beneficiary of new forms of conservation. Cheap sensors, mobile phones, and acoustic signals could provide input data from which AI could identify the best and cheapest ways of preserving life-forms of all kinds in what he calls an Internet of Life (as opposed to the Internet of Things). The benefits would be substantial. To take just one example, African elephants are estimated to provide $1.75 million per animal, or $700 billion for the whole continent.

Ledgard's vision goes beyond advocating for the funding of charismatic animals. He envisages a whole new financial ecology that is built around an understanding of the needs and preferences of nonhumans revealed by their behavior. Just as cash transfers are becoming an instrument of choice for reducing human poverty, Ledgard proposes a Financial Trust that will be devoted to programs that support the survival and prosperity of a range of nonhumans. The science of what is necessary to stem mass extinctions exists and is rapidly improving. It has to be implemented effectively.

Applications Development

Frontier technologies can only realize their potential if they solve practical problems on the ground. Not all technologies are equally relevant in all geographies. For example, an agricultural technology that helps one type of crop grow in one part of the world might be irrelevant in another part of the world with a different agro-ecology. Moreover, as several of the following chapters note, technology adoption is highly dependent on economic, regulatory, and social factors. Liberia has provided a positive example of this during the COVID-19 pandemic. Despite the country's very low average income levels, strong political leadership was able to mobilize trusted health workers—already embedded in communities—to help contain virus transmission through a range of public health tools that used the new technologies. In Senegal, farmer groups already collaborating for marketing and sourcing of seeds and other agricultural inputs have become collective owner-operators of shared solar power systems, which have proven to be a key approach to scaling up solar power with ample storage. The broader lesson is that applications need to account for local context, and preferably be developed locally, if new technology is to have a scaled-up impact.

In adapting to a local context, new technologies also often need to have kinks taken out. An instantaneous smash hit is far less common than a cycle of good idea and innovation, followed by a temporary period of disillusionment when there can be setbacks and failures (remember Tesla's exploding batteries), then a steady rollout of improvements and applications, and finally a maturation and slowdown of diffusion as the market gets saturated. This basic framing was introduced by Everett Rogers as far back as 1962, in his book *Diffusion of Innovation*.[30]

Within this cycle, the period when impact is greatest is during the improvements and applications phase. This is particularly the case for applications of so-called general-purpose technologies, which affect many industries. Economist Robert Gordon, in his monumental work *The Rise and Fall of American Growth*, documents a twenty-year time lag between Edison's electric light bulb and the mass uptake in American cities after 1900.[31] The waiting period for the twenty-first-century technology of digital platforms and AI, dubbed the Fourth Industrial Revolution by World Economic Forum Chairman Klaus Schwab, is still ongoing. One big question is if and when it will reach the stage of widespread improvements and applications.

Several of our chapter authors feel this stage is imminent. In chapter 6, Tarek Ghani and Grant Gordon describe AI's potential to anticipate, respond to, and recover from crises. Research into the long-run determinants of economic growth systematically shows that countries that have the fewest episodes of slow growth, and the shallowest recessions, have the fastest long-run growth.[32] In other words, avoiding crises is the best recipe for achieving long-run prosperity. Ghani and Gordon suggest that machine learning applications will permit analysts to assess the risks of new and ongoing crises, especially the risk of natural disasters, which cost the world US$210 billion in 2020, of which about half was in developing countries.[33] Better and earlier prediction can then lead to better targeting and service delivery mechanisms. These, in turn, would permit new insights into how resources, including financial resources, can be pre-positioned so as to be

30. Rogers.
31. Gordon (2016).
32. Commission on Growth and Development.
33. Munich Re.

accessible as quickly as possible. Humanitarian workers have known for a long time that rapid response is critical for mitigating the impact of natural disasters.[34]

In similar vein, in chapter 7, Lesly Goh looks at the potential for transforming smallholder agriculture. Long regarded as technologically backward, with few innovations, at least compared to manufacturing or services, agriculture could be on the cusp of a new productivity revolution. The driver is not just new seeds and technologies—although these are on the horizon, too—but new digital platforms connecting smallholder farmers with customers in a far more direct fashion than the slow chain of passing through numerous middlemen. Goh's maxim is "think big, act fast, start small." She documents the huge gains in farm productivity that can arise from higher price transparency, better matching of supply and demand, better farmer access to finance, and data collection and analytics to improve agronomic decisions such as fertilizing, watering, and harvesting. She discusses the new business models already being adopted to harness AI's potential and offers some recommendations as to how public-private partnerships can jump-start these smallholder innovation ecosystems in developing countries.

Quick response is also needed for combating tropical deforestation. In chapter 8, Hiroaki Okonogi, Eiji Yamada, and Takahiro Morita look at this across contexts of the Amazon and Congo Basins and in Southeast Asia. They propose scaling up new technologies to improve our "Eyes on the Planet." Based on extensive field experience, they show that the loopholes through which unscrupulous actors continue to cut trees can be closed by vigorous implementation of new technologies. Cloud cover, which prevents optical satellites from identifying areas of deforestation, can be penetrated by new radar satellites using radio waves, and these are becoming more sophisticated and able to detect illegal deforestation in a more granular way. Knowing where the forest is being cut, however, is only one step in the process of slowing down illegal operations. The next steps are to alter incentives and accountabilities of large companies by combining imagery with better forest governance and providing data to local stakeholders to use as their own surveillance tool in enforcing their rights.

The emphasis on how people respond to applications is taken up in chapter 9 by Tomoyuki Naito on "smart cities." Naito argues that smart cities have evolved from demonstration showcases of new technologies, especially in transport and environmental areas, to data-driven societies where sensors and cameras collect large amounts of data that is analyzed by AI to come up with solutions to human problems. The smart city commercial industry is already worth some US$80 billion and is doubling in size every three years. The gains could be very substantial, not least because, as UN secretary-general Antonio Guterres has remarked, "the

34. Knoll.

only place where we really have a clear picture about what the people really want is when we work at the local level and municipal level."[35] A breakthrough on smart cities is now possible if we are able to combine visionary technology with good governance and citizen-level collaborations and partnerships.

Systems Change

Technological change does not only come in the form of products. A great deal occurs through small, incremental improvements in processes. Incremental change is good when improving efficiency in a steady way, but sometimes change has to be wholesale, discarding current practice and creating a new system. This kind of systems change, sometimes known as radical change, calls for a total redesign.

Themes of systemwide alignment—and realignment—appear throughout this volume: technologies, policies, regulatory treatment, infrastructure, and partnerships among governments, NGOs, and private companies. The focus is less on the technology itself, or even on how it is applied, and more on how it can be embedded into new ecosystems and platforms that, in turn, learn how to learn and adapt.

For any market economy, money forms one of the most fundamental building block systems, having probably emerged around five thousand years ago. Paper money, issued with the monopoly right of the state, was introduced about a thousand years ago. But as Tomicah Tilleman writes in chapter 10, "cash is so insecure that responsible regulators would likely never approve it for use today if it were proposed as a new medium of exchange." His vision is that a new digital payment architecture is on the horizon, one that will permit fast, inexpensive, secure, and inclusive payments for all. He documents enormous efficiency benefits from reducing waste, fraud, and abuse in public finance, and additional indirect benefits from the expansion of economic activity that results whenever transaction costs go down. His big concern is with the control or governance of such a new system, with objections to centralized structures operated by governments or where financial information is owned and controlled by large tech firms. But new open-source platforms can mitigate such risks and make digital payments into a new type of a global public good.

How do we get big changes like this? The ideas of social entrepreneurship, mainstreaming social purpose into business activity, are now well accepted, and a large ecosystem of social entrepreneurs is helping implement these ideas throughout the world. Bright Simons wants to take this to the next level, in

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chapter 11. Rather than having an army of social entrepreneurs, who often serve as intermediaries between key nodes in an economic network, he calls for an army of systems entrepreneurs who can help reshape the relations between nodes in the same networks. These people would start from the premise that many of the obstacles to using new technologies come from points where social interactions are important. When systems need to be changed, and individual behavior needs to change, outcomes can move in many different directions. In the new "transmediation" techniques he identifies, relationships among different players can be recast with the help of sophisticated digital algorithms but with agility to respond to changing circumstances. Using the powerful example of Agrotrack, Simons showcases a new way of designing solutions, a new way of breaking down interconnected barriers, and a new way of using technology innovation systems.

Getting the design principles right is also the theme of Ann Mei Chang's concluding chapter in this volume. The biggest breakthrough, in her words, would be "a new approach to innovation, not yet another new technology." It is encouraging that there is a growing consensus on what such a new approach could be. The Whistler principles to accelerate innovation for development impact are a starting point that stress the real needs of real people, an understanding of the problem at hand, before any attempt to come up with a solution. As an example, the simple technology of community radio has provided life-saving information in Ethiopia's COVID-19 response. Building in feedback loops and designing for scale at the outset are other design principles for systemwide impact. The real breakthrough, however, will come when more effort is put into open-source platforms with common infrastructure and tools. Rather than developing end-to-end solutions from scratch, a design ecosystem, on which myriad new problem-solvers can build, is needed. This new approach is already underway, giving confidence to the potential for new breakthroughs in addressing the SDGs, even if we cannot predict where these will come from right now.

Imagining the Future

The contributors to this volume have identified technologies with the potential to achieve huge scale and huge impact over the coming decade. Without such technological breakthroughs, there is no chance of achieving the SDGs. For example, even before COVID-19, the pace of extreme poverty reduction had slowed rapidly because economic growth—the most effective technology system for poverty reduction—had faltered in some of the poorest countries. The pandemic has only heightened the range of uncertainty for outcomes in 2030.

Breakthroughs represent the step changes that kick off new cycles of positive change. Initially, the pace of change and impact might be slow, so emergent trends can be hard to spot. There are often many false leads and overhyped narratives of promising technologies that fail to live up to their billing. It takes an expert in the field to sort out what could really make a difference. That is exactly what the contributors to this volume have done, across their respective fields of expertise.

A focus on technology prompts awareness of how different the world could soon be. According to our experts, the world in 2030 could:

- Anticipate and mitigate health pandemics originating in any country
- Make fertilizers and pesticides from microbes, not petroleum, and grow leather from mushrooms
- Have solar power that is too cheap even to meter, at least at some times of the day
- Provide money in trust for nonhumans, as a way of driving the direction of nature conservancy
- Create tools to transform (and predict need for) the response to natural and man-made crises
- Link millions of smallholder farmers directly with technology platforms and market information
- Monitor deforestation in real time to allow rapid pursuit of criminals
- Move "smart cities" from slogan to reality, underpinned by ethical data governance
- Have safe, universal access to financial services and save trillions of dollars annually by eliminating fees
- Scale social entrepreneurs into systems entrepreneurs, transforming entire social systems
- Incentivize smart risks in funding technological breakthroughs

Altogether this frames an inspiring vision rather than a prediction. The process of technological change can be difficult. There are often winners and losers, and people will fight hard to avoid a sense of loss. From a business perspective, change for the SDGs must confront vested interests and retain competitive markets. From a societal perspective, acceptable new technologies must empower people, reduce inequality, and protect privacy, while building trust in government, science, and other institutions.

A final note of caution is important, too. Most of the technologies considered in this volume rely heavily on large-scale data processing, inevitably raising the issue of how data can be governed in an ethical way. For example, the use of AI for crisis prevention and mitigation can reduce suffering and damage, but it relies on imperfect algorithms. Moreover, machine learning processes might be trained by low-quality data. As a result, "precision social service delivery" may fail in delivering on its underlying intentions and might lack democratic checks on its generated outcomes. High levels of detail might be inconsistent with data privacy. Issues of bias, quality, feedback, and consent all need to be addressed to foster confidence in results-based learning. It is crucial for citizens to be engaged on how their data is managed and used.

Humility is essential, too. Technology does not solve problems on its own. It must advance, align, and succeed with its community and society of users. New technologies need to be accompanied by clear-headed debates about why they are needed, how they work, and who will ultimately benefit. Sometimes the answers will be hard to pin down. Somethings they will be highly context-specific.

A belief in technology's power to fuel SDG progress does not benefit from any underestimate of the challenge. Each step forward in advancing science, developing applications, and building systems will require many forms of human ingenuity, resourcing, and persistence. When a critical mass of key ingredients comes together, the overall odds of a breakthrough become much higher. There is no guarantee of progress. But imagining the opportunity forms a first step toward achieving a world of sustainable development for all.

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