and more immediate gains from the continued advance of robotics and artificial intelligence in the economy. Looking at data across the Group of 20 industrialized countries, a simulation prepared by the IMF staff points to the risk of declining labor shares, income polarization, and rising inequality. This assumes substantial transition costs (unemployment, lower wages) as increasing automation substitutes for and displaces existing human labor.

However, applying this same approach only to Japan yields some very different results. Specifically, with a shrinking labor force, even fully substitutable automation could boost wages and economic growth. In other words, with labor literally disappearing and dim prospects for relief through higher immigration, automation and robotics can fill the labor gap and result in higher output and greater income rather than replacement of the human workforce.

These positive results notwithstanding, Japan is not immune from societal and welfare risks linked to increased automation. Polarization of the labor force, in which a relatively small proportion of workers have the training and education needed to fully leverage productivity from robotics, is always a social risk. Research suggests that the female labor force, which has swelled in the past five years, is particularly vulnerable to displacement, given the heavy concentration of women in nonregular jobs (that is, temporary, part-time, or other positions outside the mainstream of Japan's lifetime employment system), whose tasks are more susceptible to automation (Hamaguchi and Kondo 2017).

Domo arigato, Mr. Roboto?

There is no crystal ball that can accurately predict how fast and how far robotics and artificial intelligence will advance in the next few decades. Nor is there perfect foresight with regard to how these technologies will be adapted to substitute for human labor—particularly in sectors outside of manufacturing. Aside from the nontrivial technological challenges, there are a range of hurdles related to supporting infrastructure—including the legal framework for the use of such technologies alongside the general population—that will need to be worked out. Key issues could include consumer protection, data protection, intellectual property, and commercial contracting.

But the wave of change is clearly coming and will affect virtually all professions in one way or another. Japan is a relatively unique case. Given the population and labor force dynamics, the net benefits from increased automation have been high and could be even higher, and such technology may offer a partial solution to the challenge of supporting long-term productivity and economic growth. Japan's experience could hold valuable lessons for such countries as China and Korea, which will face similar demographic trends in the future, and for Europe's advanced economies.

For policymakers, the first hurdle is to accept that change is coming. The steam engine was likely just as disconcerting, but it came nonetheless—putting an end to some jobs but generating many new ones as well. Artificial intelligence, robotics, and automation have the potential to make just as big a change, and the second hurdle may be to find ways to help the public prepare for and leverage this transformation to make lives better and incomes higher. Strong and effective social safety nets will be crucial, since disruption of some traditional labor and social contracts seems inevitable. But education and skills development will also be necessary to enable more people to take advantage of jobs in a high-tech world. And in Japan's case, this also means a stronger effort to bring greater equality into the labor force—between men and women, between regular and nonregular employees, and even across regions—so that the benefits and risks of automation can be more equally shared. FD

> The proliferation of robots will extend well beyond Japanese factories to include schools, hospitals, nursing homes, airports, train stations, and even temples.

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BUILDING TALLER LADDERS

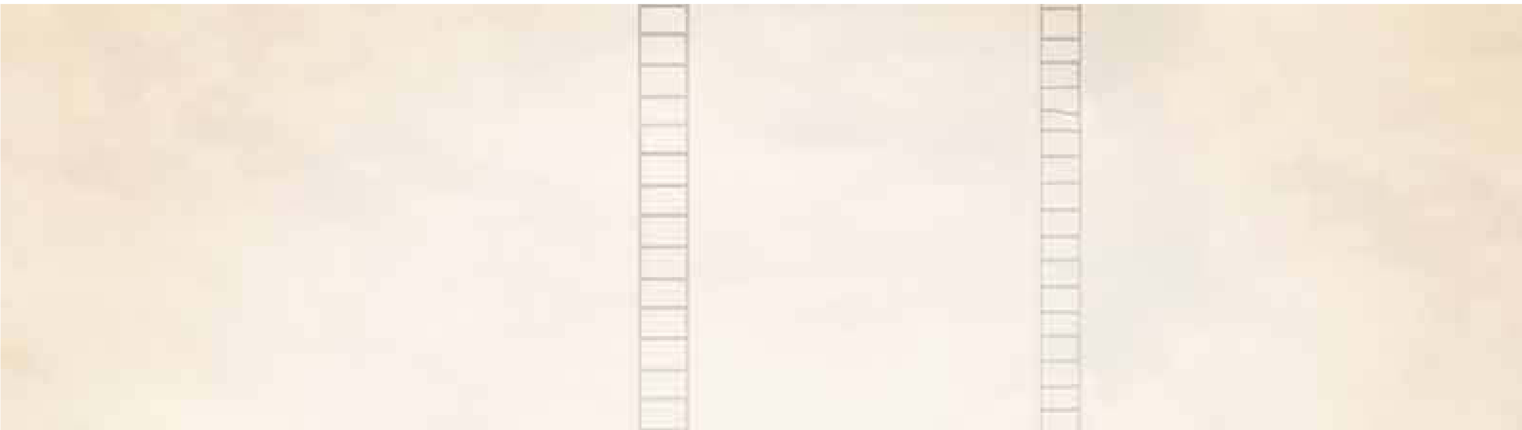
Technology and science reinforce each other to take the global economy ever higher

Joel Mokyr

In recent years, many economists have questioned the ability of technological progress to keep propelling the economy forward despite declining population growth and rising dependency ratios (Gordon 2016). According to those in this camp, the low-hanging fruit have mostly been picked, and further advances will become increasingly difficult (Bloom and others 2017).

Others would counter that science allows us to build taller and taller ladders to reach ever-higher-hanging fruit. Based on rapidly improving scientific insights, technological breakthroughs still have the potential to change life in the foreseeable future as much as they did in the century and a half since the US Civil War, proponents of this view contend.

Why is it plausible that scientific progress will continue to advance? Technological progress does not just affect productivity directly; it also pulls itself up by the bootstraps by giving science more powerful tools to work



with. Humans have limited ability to make highly accurate measurements, to observe extremely small objects, to overcome optical and other sensory illusions, and to process complex calculations quickly. Technology consists in part in helping us overcome the limitations that evolution has placed on us and learn of natural phenomena we were not meant to see or hear—what Derek Price (1984) has called "artificial revelation." Much of the 17th century scientific revolution was made possible by better instruments and tools, as exemplified by Galileo's telescope and Hooke's microscope.

Scientific progress in the modern age was similarly dependent on the tools at the disposal of researchers. A combination of improved microscopy and better lab techniques made possible the discovery of the germ theory, arguably one of the greatest medical advances of all time. In the 20th century, the number of examples that demonstrate the impact of better instruments and scientific techniques multiplied. One of the greatest heroes of modern science is X-ray crystallography. The technique has been instrumental in discovering the structure and function of many biological molecules, including vitamins, drugs, and proteins. Its most famous application was no doubt the discovery of the structure of the DNA molecule, but its use has been instrumental in 29 other Nobel-Prize-winning projects.

Of the traditional tools in use in our age, the microscope is still one of the most prominent, as it is basic to the ubiquitous tendency toward miniaturization—that is, to understand and manipulate the world at smaller and smaller levels. Scanning tunneling microscopes invented in the early 1980s started research at the nanoscopic level. The more recent Betzig-Hell super-resolved fluorescent microscope, whose developers were awarded the Nobel Prize for chemistry, is to Leeuwenhoek's microscope what a thermonuclear device is to a firecracker. The same can be said for telescopy, where the revolutionary Hubble telescope is soon to be replaced by the much more advanced James Webb space telescope.

Two powerful scientific tools that have only recently become available and that represent complete breaks with the past are fast computing (including practically unlimited data storage and search techniques) and laser technology. Both, of course, have found innumerable direct applications in the production of capital and consumer goods. The impact of computers on science has gone much beyond analyzing large-scale databases and standard statistical analysis: a new era of data

> Technological progress does not just affect productivity directly; it also pulls itself up by the bootstraps by giving science more powerful tools to work with.

science in which models are replaced by powerful mega-data-crunching machines has arrived. Powerful computers employ machine-learning algorithms to detect patterns that human minds could not have dreamed up. Rather than dealing with models, regularities and correlations are detected by powerful computers, even if they are "so twisty that the human brain can neither recall nor predict them" (Weinberger 2017, 12).

But computers can do more than crunch data: they also simulate, and by so doing, they can approximate the solution of fiendishly complex equations that allow scientists to study hitherto poorly understood physiological and physical processes, design new materials, and simulate mathematical models of natural processes that so far have defied attempts at closed-form solution. Such simulations have spawned entirely new "computational" fields of research, in which simulation and large data processing are strongly complementary in areas of high complexity. Historically some scientists dreamed of such a tool, but it is only the most recent decade that will have the capability to do this at a level that will inevitably

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> If the history of the first two industrial revolutions was dominated by energy, the future may well witness truly radical progress in the evolution of new materials.

affect our technological capabilities and hence affect productivity and presumably economic welfare.

With the advent of quantum computing, computational power in many of these areas may increase by a substantial factor. By the same token, artificial intelligence, while still the source of much concern that it will replace educated knowledge workers and not just routinized jobs, could become the world's most effective research assistant, even if it will never become the world's best researcher (*Economist* 2016, 14).

Laser technology is an equally revolutionary scientific tool; when the first lasers were developed, it was said, its inventors thought it was a technique "in search of an application." But in the 1980s, lasers were already used for cooling micro samples to extraordinarily low temperatures, leading to significant advances in physics. Nowadays, the deployment of lasers in science has a dazzling range. One of its most important applications is laser-induced breakdown spectroscopy, an astonishingly versatile tool used in a wide range of fields that require a quick chemical analysis at the atomic level, without sample preparation. Lidar (light radar) is a laser-based surveying technique that creates highly detailed three-dimensional images used in geology, seismology, remote sensing, and atmospheric physics and recently helped radically revise upward our estimates of the size and sophistication of pre-Columbian Maya civilization in Guatemala. But lasers are also a mechanical tool that can ablate (remove) materials for analysis. For laser ablation, any type of solid sample can be ablated for analysis; there are no sample-size requirements and no sample preparation procedures. And laser interferometers have been used to detect the gravitational waves Einstein postulated, one of the most sought-after discoveries of modern physics.

Century of biology

Yet there is far more. As Freeman Dyson has remarked, if the 20th century was the century of physics, the 21st century will be the century of biology. Recent developments in molecular biology and genetics imply revolutionary changes in humans' ability to manipulate other living beings. Of those, the ones that stand out are the decline in the cost of sequencing genomes at a rate that makes Moore's Law look sluggish by comparison: the sequencing cost has declined from $95 million per genome in 2001 to about $1,250 in 2015.

Especially promising is the technique to *edit* a base pair in a genetic sequence, thanks to recent improvements in CRISPR Cas9 techniques. The other is synthetic biology, which allows for the manufacturing of organic products without the intermediation of living organisms. The idea of cell-free production of proteins has been around for about a decade, but only recently has its full potential become known to the public, even if its realization is still years away.

Symbiotic relationship

Ecclesiastes notwithstanding, there is much under the sun that is entirely new. If the history of the first two industrial revolutions was dominated by energy, the future may well witness truly radical progress in the evolution of new materials. Naming an economic epoch after its dominant raw material ("the Bronze Age") is an age-honored habit among historians. Many technological ideas in the past could not be realized because the materials that inventors had available were simply not adequate to make their designs a reality. But recent science-driven advances in material science allow scientists to design new synthetics that nature never had in mind. Such artificial materials, developed at the nanotechnological level, promise the development of materials that deliver custom-ordered properties in terms of hardness, resilience, elasticity, and so on. New resins, advanced ceramics, new solids, and carbon nanotubes are all in the process of development or perfection.

Artifical intelligence, lasers, and genetic engineering seem to qualify as general purpose technologies (GPTs) that have many applications across a wide spectrum of uses in production and research.