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Views & Comments

On the Future: A Keynote Address

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Editor's note: *The following commentary is based on the keynote speech Professor Lord Martin Rees, the United Kingdom's Astronomer Royal, presented at* Engineering in an Unpredictable World: The Global Grand Challenges Summit 2019 *in London on 18 September 2019. This and other talks at the Summit are available to watch at:* https://www.raeng.org.uk/policy/partnerships/international-policy-and-development/ggcs/2019/welcome/on-demand-2. *Based at the University of Cambridge, Lord Rees is a cosmologist and astrophysicist, a philosopher of science, and a former President of the Royal Society. Besides his countless scientific papers, Lord Rees has written a wide range of books, from academic texts to best-selling popular science. The content of Lord Rees's speech was drawn from his most recent book,* On the Future: Prospects for Humanity, *published in 2018* [1]. *A Chinese translation of the book will be available in 2020.*

People who hear that I have the title "Astronomer Royal" have been known to ask me: "Do you do the Queen's horoscopes?" I tell them I am an astronomer, not an astrologer. Scientists are rotten forecasters, almost as bad as economists. So, my predictions of the future are necessarily tentative, and are balanced between scientific optimism and political pessimism.

My central theme is that although our Earth has existed for 45 million centuries, this century is special. It is the first in which one species has the planet's future in its hands. We are deep in the Anthropocene, and I shall give you a tour of its technological front lines.

But I shall focus first on two things we can predict even with a cloudy crystal ball: the world in 2050 will be more crowded, and it will be warmer. Fifty years ago, the population was about 3.5 billion. It is now about 7.7 billion, with the growth mainly in Asia and Africa. Globally, the number of births per year peaked in 2012, and birthrates are now dropping in most countries [2]. But the world population could still rise to about 10 billion by 2050, in part because the majority of people in the developing world are young, have not yet borne children, and are likely to live longer than the generation before them (Fig. 1) [3].

Despite grim forecasts to the contrary in the 1960s, food production has kept pace with the rising population. Famines still occur, but they are due to conflict or maldistribution, not overall scarcity. As Gandhi observed, there is enough for everyone's need, but not for everyone's greed. Feeding ten billion people in 2050 will require further-improved agriculture, including genetically modified crops. Dietary innovations may also play a role, such as artificial meat or converting nutritious insects into palatable food.

Population levels beyond 2050 are uncertain. Falling infant mortality, urbanization, and improved education for females all foster a demographic transition toward lower birth rates. But there could be countervailing cultural influences. If families in Africa remain large, the UN predicts that the continent's population could double again between 2050 and 2100, to four billion, thereby raising the global population to 11 billion [4]. Nigeria alone would by then have a population comparable to those of Europe and North America combined. Wealthy nations, especially those in Europe, should urgently promote the growth of prosperity in Africa, and not purely for altruistic reasons.

The geopolitical stresses ahead are worrying. Those in poor countries now know, largely courtesy of the Internet, what they are missing, and migration is generally easier. This is a recipe for disaffection and instability—multiple mega-versions of the tragic refugee "boat people" crossing the Mediterranean today, with many dying in the process [5].

If humanity's growing numbers continue to impact land use, and if global temperatures rise unabated, the resultant shock to the ecosphere means that we could be destroying the book of life before having the chance to read it. We have already skewed things enormously: there is now more biomass in chickens and turkeys than in all the world's wild birds [6], and the combined biomass of humans and livestock is about 20 times that of all wild mammals put together [7]. For many environmentalists, preserving the richness of our biosphere has value in its own right, but it is also an undeniably crucial component of human wellbeing. To quote the great ecologist E. O. Wilson: "Mass extinction is the sin that future generations will least forgive us for."

Feeling the heat

Here's a second firm prediction: it will get warmer (Fig. 2) [8]. In contrast to population issues, climate change is not underdiscussed, but it is certainly under-responded-to. The urgent need for action was re-emphasized by the Intergovernmental Panel on Climate Change in a special report published in October 2018 [9].

The challenge of prioritizing action comes in part from the very nature of economic theory, which heavily discounts the future. As a result, standard economic models essentially ascribe no value to what happens after 2050. Thus, even people who agree that there is a big risk of climate catastrophe a century hence will differ in

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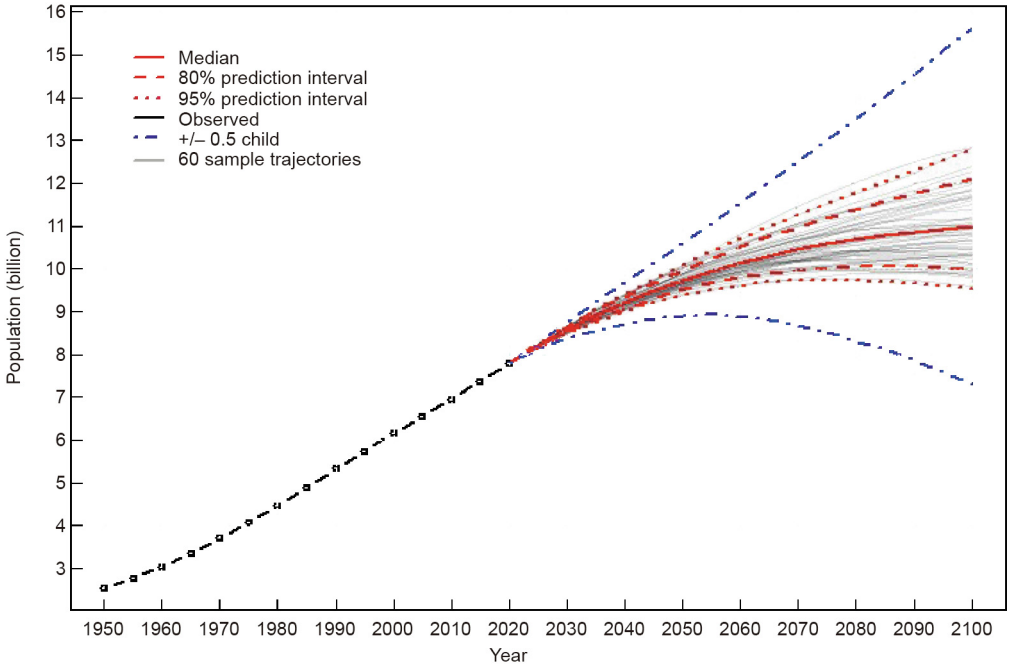

Fig. 1. A population of 11 billion people by 2100, predicted by the United Nations' Population Division, will present an enormous challenge to the planet, and to human ingenuity. Reproduced from Ref. [3], ©2019 United Nations, Department of Economic and Social Affairs, Population Division (CC BY 3.0 IGO).

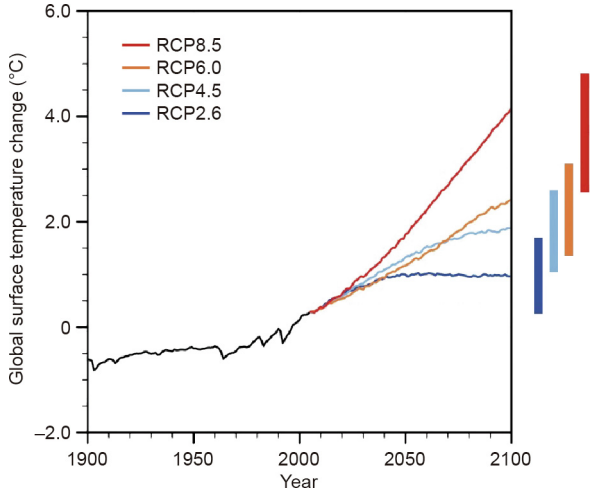

Fig. 2. With annual global greenhouse gas emissions still rising, the world will continue to warm, but by how much? The Intergovernmental Panel on Climate Change projects a range of possible outcomes based on a set of potential future emission scenarios—Representative Concentration Pathways (RCP)—increasing from dark blue to red. Vertical bars on the right represent likely ranges for global temperature change for each RCP by the end of the 21st century. Reproduced from Ref. [8], FAQ 12.1, Fig. 1; United Nations, Intergovernmental Panel on Climate Change (CC BY 3.0 IGO).

how urgently they advocate for action today. Their assessment will depend on expectations of future growth, and optimism about technological fixes. But, to my mind, the urgency of action on climate change depends on an overarching ethical question: should we be optimizing our lives at the expense of future generations?

As a side note, there is one policy context in which essentially zero discounting is applied: in radioactive waste disposal, depositories are required to prevent leakage for 10 000 years [10]. This is ironic, given that we cannot plan energy policy even 30 years ahead.

But there is one win-win roadmap to a low-carbon future. Nations should accelerate research and development into all forms of low-carbon energy generation, and into other technologies where parallel progress is crucial, such as smart electricity grids and energy storage—batteries, compressed air, pumped storage, flywheels, and so on.

The faster these cleaner technologies advance, the sooner their prices will fall, making them affordable. This will be especially important to countries such as India, where more generating capacity will be needed, where the health of the poor is jeopardized by smoky stoves burning wood or dung, and where there would otherwise be pressure to build coal-fired power stations.

Sun and wind energy are front-runners, but other generation methods have geographical niches. For example, tidal energy is attractive where there are especially large-amplitude tides, as on Britain's west coast. Indeed, there are proposals for tidal barrages or lagoons there.

Because of the local intermittency of the sun and wind, we will need continental-scale DC grids. These would carry solar energy from the south in Morocco and Spain to the less sunny Northern Europe, and from east to west, in order to smooth peak demand over different time zones in North America and Eurasia, perhaps all the way along the Belt and Road to China.

And despite ambivalence about nuclear energy, it is surely worthwhile to boost research and development into a variety of "Generation IV" power station concepts, which could prove to be more flexible in size and safer [11]. Furthermore, the potential pay-off from fusion is so great that continuing experiments and building prototypes makes good sense.

This research and development scenario offers a win-win option for the United Kingdom, too. If the nation hits its legally mandated target of becoming carbon-emissions neutral by 2050 [12], global emissions will drop by less than 2%. But we produce about 10% of the world's best scientific research. By leading in innovation, the United Kingdom can aspire to make far more than 2% difference. It would be hard to think of a more inspiring challenge for young scientists than devising clean and economical energy systems for the world.

Double-edged swords

We should be evangelists for new technology—without it, the world cannot provide food and sustainable energy for an expanding, more demanding population. But our future will require wisely directed technology. Indeed, many of us are anxious that technology is advancing too fast for us to cope with it sensibly, and that we have a bumpy ride ahead.

In healthcare, splendid advances in microbiology—diagnostics, vaccines, and antibiotics—offer prospects of containing pandemics. But these same advances will strengthen concerns about the safety of experiments, the dissemination of "dangerous knowledge," and the ethics of how biotechnology is applied. In 2011, for example, research groups in Wisconsin, USA, and the Netherlands showed that it was possible to make the influenza virus both more virulent and more transmissible [13]. To some, this was a frightening portent of things to come.

The new CRISPR/cas9 technique for gene editing is hugely promising, but there are already ethical concerns, for example, regarding experiments modifying human embryos [14], and anxiety about possible runaway consequences of "gene drive" programs to wipe out species such as mosquitos or grey squirrels [15].

Governments will surely adopt a stringent and precautionary attitude to biotechnology. Yet whatever regulations are imposed, they simply cannot be enforced worldwide—any more than drug or tax laws can. Whatever *can* be done *will* be done by someone, somewhere. And that is a nightmare. While nuclear bombs cannot be built without huge, conspicuous special-purpose facilities, biotechnology involves small-scale, dual-use equipment. Indeed, biohacking is burgeoning even as a hobby and competitive game [16]. These concerns are relatively near-term—within the next ten or 15 years. It is difficult to even imagine what may be possible in 2050 and beyond.

Artificial intelligence

The smartphone, the Internet, and their ancillaries—which are ubiquitous today—would have seemed magical even 25 years ago. So, looking several decades ahead, we must keep our minds open (or at least ajar) to transformative advances that may now seem like science fiction.

On the biology front, we might expect two things: a better understanding of the combination of genes that determine the key characteristics of humans and animals, and the ability to synthesize genomes that match these features. If it becomes possible to "play God on a kitchen table," our ecology—and even our species—may not long survive unscathed.

And what about another transformative technology: robotics and artificial intelligence (AI)? There have been exciting advances in generalized machine learning. DeepMind's "AlphaZero" AI system famously achieved world-championship level in the games of chess, shogi, and Go in a matter of hours (Fig. 3) [17]. AI can already cope better than humans with complex fast-changing networks such as traffic flow or electricity grids. In science, its capacity to explore zillions of options could allow it to discover recipes for better drugs, or perhaps room-temperature superconductors.

It is, of course, the speed of computers that allows them to succeed: they learn to identify dogs, cats, and human faces by crunching through millions of labeled images—not the way humans learn. Similarly, they learn to translate by reading millions of pages of multilingual text. In Europe, computers are fed European Union documents—their boredom threshold is infinite!

The implications of AI for our society are mixed. If we were sentenced to a term in prison, recommended for surgery, or even given a poor credit rating, we would expect the reasons to be accessible to us and contestable by us. If such decisions were entirely delegated to an algorithm, we would be entitled to feel uneasy, even if presented with compelling evidence that, on average, machines make better decisions than the humans they have usurped.

Fig. 3. The ancient Chinese game of Go was yet another bastion of human intellect overcome by artificial intelligence, in the form of DeepMind's AlphaZero system. (Photo credit: DeepMind, with permission).

AI systems will become more pervasive. Records of all our movements, our health, and our financial transactions will be in the cloud, managed by a multinational quasi-monopoly. The data may be used for benign reasons such as medical research, but its availability to internet companies is already shifting the balance of power from governments to globe-spanning conglomerates.

Robot revolution

Clearly, machines will take over much of manufacturing and retail distribution. They can also supplement, if not replace, many white-collar jobs, such as routine legal work, accountancy, computer coding, medical diagnostics, and even surgery. Many professionals will find their hard-earned skills in less demand. In contrast, some skilled service-sector jobs—plumbing and gardening, for example—require non-routine interactions with the external world and will be among the most difficult jobs to automate.

The digital revolution generates enormous wealth for innovators and global companies. But preserving a healthy society will surely require the redistribution of that wealth. In addition, to create a humane society, governments will need to vastly enhance the number and status of those who care for the old, the young, and the sick. There are currently far too few caregivers, and they are poorly paid, inadequately esteemed, and insecure in their positions. Nevertheless, I would suggest that such employment is more fulfilling than work in call centers or Amazon warehouses, which can be readily automated.

Be that as it may, society will likely be transformed by the coming wave of robots. If you believe some people, we may even become one with the robots. Leading such enthusiasts is the futurologist Ray Kurzweil. In his book, *The Age of Spiritual Machines*, he predicted that humans would transcend biology by merging with computers [18]. Kurzweil is worried that his vision may not happen in his lifetime, so he has signed up with a company in Arizona in the United States that, in the event of his untimely death, will freeze and store his body [19]. When immortality is finally on offer, this will allow him to be resurrected—or perhaps have his brain downloaded. Personally, I would rather end my days in an English churchyard than an American refrigerator.

Some insist that ageing is an inconvenient "disease" that can be cured. Or, at least, that human mentality and physique may become malleable thanks to genetic and cyborg technologies. Such secular "intelligent design" will change us far faster than Darwinian evolution did, and could be a game-changer. When we

admire the literature and artefacts that have survived from antiquity, we feel an affinity, across a gulf of thousands of years, with those ancient artists and their civilizations. But we can have zero confidence that the dominant intelligences a few centuries from now will have any emotional resonance with us—even though they may have an algorithmic understanding of how we behaved.

The final frontier

And now I turn briefly to another technological arena: space. This is where robots surely have a future, and where I would argue that these changes will happen fastest—and should worry us less.

We depend every day on space for satellite navigation, environmental monitoring, communications, and more. During this century, the whole solar system will be explored by swarms of miniaturized probes, far more advanced than the probes that have beamed back close-ups of Saturn and its moons, and of Pluto and beyond.

Think back to the computers and phones of the 1990s, when these now-distant probes were designed, and realize how much better we can do today. The next step will be the deployment in space of robotic fabricators, which can build large structures under zero gravity, such as solar energy collectors or giant telescopes with huge, gossamer-thin mirrors.

What about crewed spaceflight? The practical case for this gets ever weaker with each advance in robotics and miniaturization. I would argue that private-enterprise ventures like Elon Musk's Space X should front all crewed missions. Leave it to those courageous thrill-seekers to establish independent bases on Mars, or maybe on asteroids. Musk says he wants to die on Mars, after all—though not on impact [20].

Just don't ever expect mass emigration from Earth. Nowhere in our solar system offers an environment even as habitable as the Antarctic or the top of Everest. Here, I disagree with Musk and my late colleague Stephen Hawking. It is a dangerous delusion to think that space offers an escape from Earth's problems. Dealing with climate change on Earth is a piece of cake compared with terraforming Mars. There is no "Planet B" for ordinary people (Fig. 4).

But those pioneer adventurers who escape the Earth could be cosmically important. This is why: they will be ill-adapted to their new environment, but they will be beyond the clutches of our terrestrial regulators. They will use all the resources of genetics and cyborg technology to adapt. They will change faster and could within a few generations become a new species.

Back from the future

Let me conclude by returning to the here and now. My book, *On the Future*, emphasizes how our interconnected society is brittle and vulnerable. I would argue that we fret unduly about small risks—air crashes, carcinogens in food, low radiation doses—but are in denial about emerging threats that could be globally devastating. Some of these are environmental in nature, including the pressures of a growing, more demanding population, and others are the potential downsides of the novel technologies I have described. In the Anthropocene, a wise mantra might be: "The unfamiliar is not the same as the improbable."

And of course, most of the challenges are global. Coping with potential shortages of food, water and other resources, while transitioning to low-carbon energy, cannot be solved by each nation separately, nor can the regulation of potentially threatening innovations. Indeed, a key issue is whether nations need to give up more sovereignty to new organizations along the lines of the World Health Organization or the International Atomic Energy Agency.

Scientists and engineers have an obligation to promote the beneficial applications of their work and warn against the downsides.

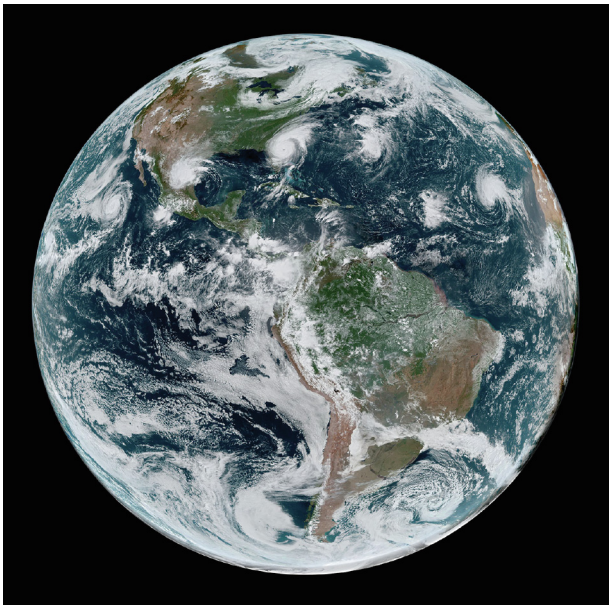

Fig. 4. There is no "Planet B" to which humanity can move *en masse* to escape the growing challenges facing us on our warming Earth, pictured here on 4 September 2019, with a loose chain of tropical cyclones spinning across the Western hemisphere. (Photo credit: NASA Earth Observatory/Joshua Stevens; NOAA National Environmental Satellite, Data, and Information Service).

Universities can use the expertise of their staff, and their convening power, to assess which scary scenarios, eco-threats, or risks from misapplied technology can be dismissed as science fiction, and how best to avoid the serious ones.

But politicians will not prioritize the global and long-term measures that are needed unless enough voters endorse such policies. So experts must enhance their leverage by involvement with non-governmental organizations, via blogging and journalism, and by enlisting charismatic individuals and the media to amplify their voice. Pope Francis's encyclical *Laudato si'* [21] had a worldwide influence in the run-up to the Paris climate conference in 2015. There is no gainsaying the Catholic Church's global reach and concern for the world's poor.

And in the United Kingdom in May 2019, I doubt the then-environment secretary Michael Gove would have become exercised about non-degradable plastic waste had it not been for the British Broadcasting *Blue Planet II* programs, presented by our secular pope, David Attenborough—particularly the images of albatrosses returning to their nests and regurgitating plastic debris for their offspring to eat [22].

It is encouraging to witness the ranks of activists rising among the young—not least the remarkable Greta Thunberg. This is unsurprising, as today's young people can hope to live to the end of this critical, special century. Their campaigning is welcome, and their commitment gives me grounds for hope.

"Spaceship Earth" is hurtling through the void. Its passengers are anxious and fractious. Their life-support system is vulnerable to disruption and breakdowns. But there is too little planning, too little horizon-scanning. We need to think globally, we need to think rationally, we need to think long-term—empowered by 21st century technology but guided by values that science alone cannot provide.

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