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Unpredictability of Science

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Gloomy Forecast for the Prophets of Apocalypse and Bright Forecast for Chemists

*Ehud Keinan**

"*They are ill-discoverers that think there is no land, when they can see nothing but sea.*"
Francis Bacon (1561–1626)

Will Homo sapiens Become an Endangered Species?

In his famous "Essay on the Principle of Population", first published in 1798, Reverend Thomas Robert Malthus portrayed a grim future for humankind: "*The power of population is so superior to the power of the earth to produce subsistence for man, that premature death must in some shape or other visit the human race*".[1] In order to prevent the horrors of famine, plagues, and wars Malthus proposed preventive measures, including abortion, birth control, prostitution, postponement of marriage, and celibacy.

Malthus criticized the notion that agricultural improvements could expand limitlessly and predicted disastrous consequences even if the population grew by 10%: "*The food therefore which before supported 7 millions must now be divided among 7.5 or 8 millions*". And these apocalyptic predictions were made when there were only 150 million people in Europe and the global population was 750 million, less than the current population of Europe.

Malthusianism influenced many generations of economists, politicians, social thinkers, and scientists, including Charles Darwin and Alfred Russel Wallace, in developing their ideas of natural selection. Malthus was not the first to express these concerns, and certainly not the last. Benjamin Franklin suggested in 1751 that the British should increase their population and power by expanding across the Americas, assuming that Europe was already too crowded.[2]

A more recent version of the Malthusian prophecy, "The Limits to Growth" (LtG, 1972), gained broad popularity, selling 30 million copies in 30 languages.[3] The book argues, "*If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next 100 years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity.*"

The LtG theoretical model is very elegant and mathematically coherent; the simulations seem to make a great deal of sense, they are easy to explain and easy to understand, and they are absolutely wrong. LtG is wrong for the same reasons John Malthus was wrong, along with many other doomsday prophets, including those who occasionally pronounce the end of the world from atop a stool in the Hyde Park Speakers' Corner.

It is quite understandable why these rather naïve ideas made much sense at end of the 18th century, when almost everybody was busy producing agricultural goods. It is much less clear why these views have retained so much popularity over two centuries after a population growth of about 1000%, when most indicators of global development of the past 60 years point in the opposite direction.[4] Not only have life expectancy and living standards increased steadily, but also world gross domestic product per capita, food production per capita, accessibility to safe water, public health, personal freedom, and human dignity. At the same time, adverse indicators have declined steeply, including world adult illiteracy, war deaths, and extreme poverty. For example, the world's poor population living on less than $1 per day has dropped from 40% to 20% between 1980 and 2001.[5]

In our day and age only 2% of the population in the developed countries produces agricultural goods, supporting not only their societies but also those of the less developed countries. Malthus couldn't have predicted that turf grass would become the largest irrigated crop in the USA, with over 40 million acres (1.9% of the land) being occupied by lawn at homes, golf courses, and parks.[6] In fact, lawn takes up more USA land and water than all other irrigated crops combined, including corn, vegetables, soybeans, fruit trees, vineyards, alfalfa, hay, pastureland, and cotton. Evidently, this is not an indicator of a starving world.

Our Major Problems

It is true that humanity faces severe global challenges and problems, which seem daunting because they cannot be easily solved today on the basis of the currently known technologies.

[*] Prof. E. Keinan
The Schulich Faculty of Chemistry
Technion—Israel Institute of Technology
Technion City, Haifa 32000 (Israel)
and
The Scripps Research Institute
10550 North Torrey Pines Road, La Jolla, CA 92037 (USA)

The following six problems are well defined by the EuCheMS Roadmap:[7]

Energy. We consume enormous amounts of energy in the form of fuels, heat, and electricity. Currently, over 85 % of the world's primary energy supply is provided by fossil fuels (81 %) and uranium minerals (5.9 %).[8] The global energy demand is expected to double by 2050 because the human population is expected to increase from 7 to over 9 billion people and because of the enhanced economic growth in developing countries. The global fossil and fissionable mineral resources will be severely depleted by 2050 although coal will last for many hundred years and fossil fuels locked in shale and sands are also rather abundant. Moving to thorium as a fissionable fuel may give us several hundreds of years of nuclear energy.

Raw materials. While the importance of oil and gas has often been highlighted, the essential role of non-energy resources such as minerals and metals has received less attention. Almost every downstream industry is highly dependent on these materials. For example, cars, flat-screen monitors, and countless other products rely on antimony, cobalt, lithium, tantalum, tungsten, and molybdenum; solar panels require indium, gallium, selenium, and tellurium; many catalysts are based on nickel, palladium, platinum, and other metals, and the demand is ever increasing. Over the past 25 years the global extraction of natural resources has increased by 45 %.[7] Due to poor recovery and recycling, many elements are left inside discarded products in landfills or are being dispersed in the environment in small quantities that cannot be reclaimed. Moreover, the resources are not evenly distributed. Over 90 % of rare earths and antimony, and 75 % of germanium and tungsten come from China, 90 % of niobium from Brazil, and 77 % of platinum from South Africa. The EU has identified 14 raw materials, already regarded as "endangered species", which face potential shortages with a vast economic impact.[9]

Water. Although 71 % of the Earth's surface is covered by water, 97 % of the resource is saline, and the currently available desalination technologies are prohibitively expensive for most of the world. The remaining 3 % is fresh water, of which 90 % is locked away in glaciers, the polar ice caps, and inaccessible groundwater. Humanity's growing needs must therefore be met with only 0.3 % of the amount of water on Earth, which is renewable and stored in aquifers, surface waters, and the atmosphere. About 80 % of the world's population lives in areas with threats to water security,[10] including regions of intensive agriculture and dense populations in the USA and Europe. Over 1.8 million people die every year from drinking contaminated water and many more die from lack of water for agricultural crops and livestock.

Food. Water scarcity has a direct impact on food security. Indeed, many countries cannot support irrigated agriculture at levels necessary to feed their growing populations. Soil erosion and degradation, especially in tropical and subtropical environments, also threaten the continued productivity of agricultural lands. Overfishing threatens to damage fisheries, denying many developing regions an important source of protein. Nonetheless, most recent assessments suggest that global food production outstrips the rising global demand.[11] There is less optimism about the prospects for reducing undernutrition. Even if global food supplies are adequate, the inability of poor nations and poor families to pay for imported food in addition to difficulties in food distribution due to political upheaval means that many people will continue to go hungry. The UN Food and Agriculture Organization (FAO) identified 27 countries as having low or critical food security indexes.[12]

Health. The general indicators of human health over the past several decades show that people have become healthier and wealthier and live longer.[13] However, improved levels of health in many parts of the world are coupled with growing health inequalities in others. The nature of health problems is also changing; ageing and the effects of ill-managed urbanization and globalization accelerate the worldwide transmission of communicable diseases, and increase the burden of chronic disorders. Infectious diseases account for over a fifth of human deaths worldwide.[14] In addition to the appearance of new infectious diseases, such as SARS, and the exacerbation of current diseases through climatic change, we also face the challenge of antibiotic resistance. Chronic diseases, including cardiovascular diseases, cancer, chronic respiratory diseases, diabetes, neurodegenerative diseases, brain disorders, and others caused 35 million premature deaths globally in 2005 and this figure is expected to increase in the near future.[15]

Air. The main environmental impacts of air pollution are acidification of the oceans and soil and climatic changes through the greenhouse effect caused by carbon dioxide, methane, fluorocarbons, nitrogen oxides, and ozone. Air pollution is a significant risk factor for multiple health conditions, mainly respiratory infections, heart diseases, and lung cancer. The most common health-related air pollutants are particulate matter, ozone, nitrogen dioxide, and sulfur dioxide. The World Health Organization (WHO) states that 2.4–3.3 million people die each year from causes directly attributable to outdoor and indoor air pollution.[16] Causes of deaths include aggravated asthma, emphysema, lung and heart diseases, stroke, and respiratory allergies. In fact, more deaths are caused by air pollution than by automobile accidents.[17] The WHO reports that the greatest concentrations of particulate matter are found in countries with low economic power and high poverty. Yet, even in the USA, despite the Clean Air Act of 1970, in 2002 at least 146 million Americans were still living in non-attainment areas where the concentration of certain air pollutants exceeded federal standards.[18] In addition, excessive CO_2 emission from the use of fossil fuels may lead to global warming with unpredictable economic and social consequences.[19]

It should be noted that although the above problems are identified as separate challenges they are all interconnected. For example, new approaches to cheap energy would lead to affordable water desalination, which would affect food production.

The Unpredictability of Science

These are severe problems indeed. Nevertheless, the main reason for my optimism is the confidence that these challenges will be met by unforeseen technologies. The totally unpredictable nature of science was less obvious at the time of Malthus but it is much more apparent 200 years later. We all, including professional futurists, have no idea what our world will look like in 50 years, or even in 10 years. This is true also for commercial products. Before 1990 no one would have envisioned such a thing as the World Wide Web. Nobody could have predicted five years ago that Apple Inc. would invent and sell 500 million iPhone and iPad devices, product categories that were not in existence prior to 2007.

Most of the great inventions of the 20th century, which have changed our lives forever, emerged completely serendipitously.[20] X-ray technology, radio-astronomy, lithium-ion therapy for manic depression, the anticancer drug cisplatin, electrically conducting polymers, genetic fingerprinting, PCR technology, and charge-coupled devices (CCDs), to name a few.

Politicians who still believe that appropriate committees of experts can predict science and technology should learn about the expert commission set up in 1937 by President Roosevelt to advise him of the important technical and industrial developments expected in the subsequent 20–30 years. The Roosevelt commission failed to predict all major discoveries, including nuclear energy by fission and fusion, radar, lasers, transistors, integrated circuits, magnetic resonance imaging, tomography, personal computers, laser disks, compact disks, jet aircrafts, rocketry, space travel, fax machines, mobile phones, synchrotron radiation, polyethylene, polypropylene and most other polymers, conversion of natural gas to liquid fuels, antibiotics, biotechnology, protein engineering, the structure of DNA, molecular genetics, genomics, monoclonal antibodies, the contraceptive pill, spare-part surgery, and the global positioning system (GPS)—the list is endless.

Another long list is that of esteemed experts who made profoundly erroneous predictions.[21] Lord Kelvin claimed in 1885 that "*Heavier-than-air flying machines are impossible*", and Lord Rayleigh repeated in 1889: "*I have not the smallest molecule of faith in aerial navigation other than ballooning*". Nobel Laureate Lord Rutherford said in 1933, just a few years before the Manhattan Project: "*Anyone who expects a source of power from the transformation of (the nuclei of) atoms is talking moonshine*". Astronomer Royal Sir Richard Woolley ("*Space travel is utter bilge*") and Nobel Laureate Sir George P. Thomson ("*The possibilities of travel in space seem at present to appeal to schoolboys more than to scientists*") both made their authoritative statements in 1956, just one year before the launch of Sputnik and five years before the space travel of Yuri Gagarin.

Our inability to predict the future makes a mockery of any prophecy, and doomsday prophecies in particular. Furthermore, we need to be reminded that we no longer live solely on what Nature has given us. It is estimated that more than 50% of all nitrogen atoms in our bodies came from industrial nitrogen fixation using the Haber–Bosch process. Except for a select few hunters, berry pickers, and cave dwellers we all live in artificial environments, eat genetically engineered crops and livestock, wear either synthetic or genetically modified fibers, and use man-made devices for travel. We all rely on the products of the human imagination and creativity. And unlike the natural resources, imagination and creativity have no limits.[22] Of course, we should treat our natural environment with more respect, conserve biodiversity, and save the forests and lakes, but these acts alone are not going to solve the above-described problems.

Population Explosion versus Knowledge Explosion

The human population indeed grows exponentially, doubling approximately every 50 years.[23] This growth, however, should be compared with the much steeper exponential growth of human knowledge, which doubles every 1.5 years (Figure 1).[24] If the "amount of knowledge" is defined as 1 at the time of the Roman Empire, it doubled by the time of Leonardo da Vinci, around 1500, doubled again and became 4 at the time of the French Revolution, reached 8 in 1900, 16 in 1950, 32 in 1960, and currently doubles every 1.5 years.

In comparison with the explosive growth of human knowledge, the seemingly monstrous growth of human population is actually insignificant and can be regarded in many respects as negative. Although the doubling of human knowledge every 1.5 years is a rough estimate, the accuracy of this figure does not change the consequences. If this estimate is erroneous by 10%, 100%, or even by 1000% (doubling every 15 years) it still means that the growth of the world population is much slower. It does not change the fact that there are now about 50 million scientists and engineers around the world and that their number doubles every 15 years.[24] It does not change the fact that of all scientists who ever lived throughout the entire human history, 80–90% are still alive and active!

This qualitative analysis leads to the conclusion that our above-mentioned problems will be solved by future technologies and that humankind will survive happily on this planet for many years to come.[25] Our real problems are not energy, food, water, etc., but the increasing gaps between the advanced societies and those who are left behind in the darkness of scientific and technological ignorance.

It Is All about Chemistry

Chemistry is everywhere because all sciences, except for theoretical mathematics, deal with matter, because all materials consist of molecules, and because true understanding of any system, either animate or inanimate, is a bottom-up journey. The same holds for the innovative, rational design of new systems. Chemistry, as the "central science", is a driving force that significantly impacts other disciplines, including the technological and industrial sectors.

Yet, as George M. Whitesides wrote,[26] "*…chemistry, by its culture, has been almost blindly reductionist. I am repeatedly reminded that chemists work on molecules, as if to*

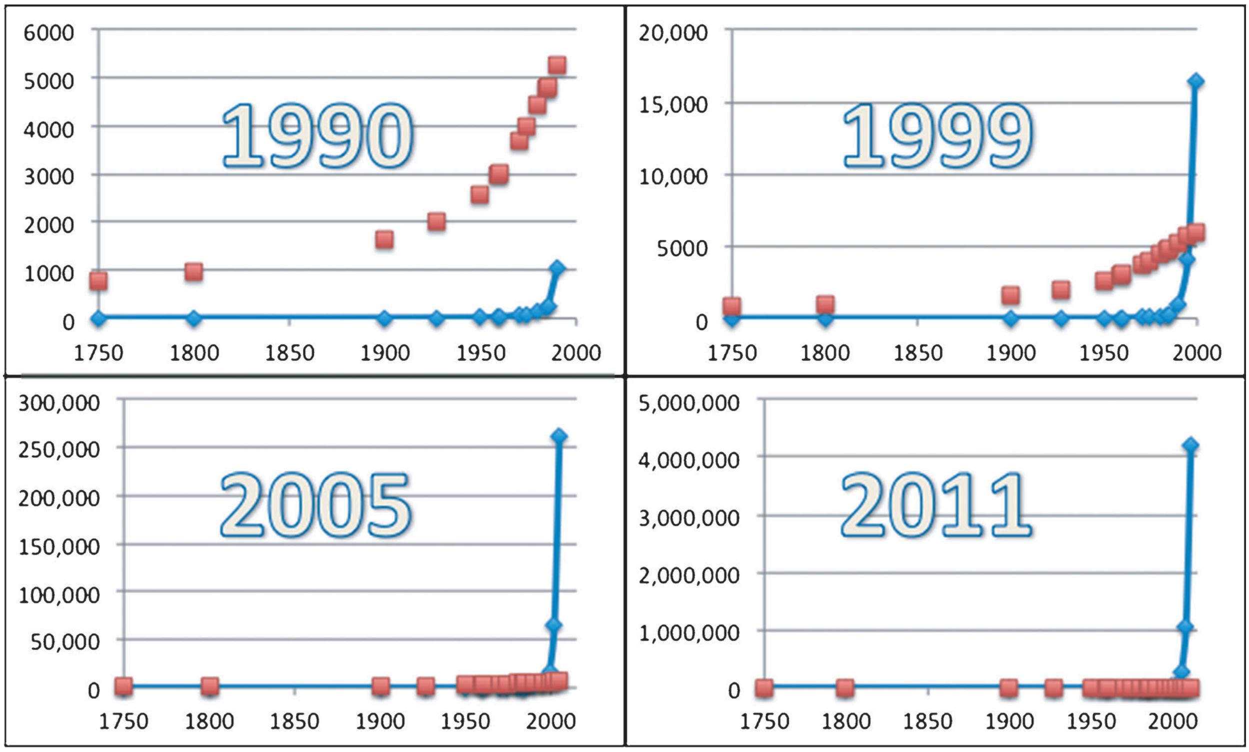

Figure 1. Plots of world population (in millions, red rectangles) and human knowledge (taken as 4 at 1750, blue diamonds) within the period of 1750–2011.

do anything else were suspect. Chemists do and should work on molecules, but also on the uses of molecules, and on problems of which molecules may be only a part of the solution. Chemistry has always been the invisible hand that builds and operates the tools, and sustains the infrastructure. It can be more. We think of ourselves as experts in quarrying blocks from granite; we have not thought it our job to build cathedrals from them."

Nobody can predict how and when the above-described problems will be satisfactorily solved. However, we can certainly predict that any solution will involve chemistry as a major component because all of these problems relate to chemistry more than to any other scientific discipline. As specified by the following comments, the chemical sciences will continue to play a central role in our journey to meet these challenges.

Energy. The total solar energy absorbed by our planet in one year is about 3850000 exajoules (EJ, 10^{18} Joules), which corresponds to more energy in one hour than the entire human consumption in one year.[27] Photosynthetic organisms capture annually only 3000 EJ of this energy.[28] Once we find ways to harness this energy with similar efficiency, fossil fuels as well as nuclear energy may no longer be needed. Understandably, current scientific and technological efforts focus on solar energy, solar electricity, and solar fuels, as well as on biomass energy, wind and ocean energies, energy conversion (fuel cells, hydrogen, energy efficiency, fossil fuels, nuclear energy), and energy storage (batteries, supercapacitors).

Raw materials. Chemists have the potential to develope new methods to extract resources efficiently and economically from yet inaccessible reserves, such as metals from seawater. The use of alternative technologies could help reducing our dependency on rare elements. Efficient recycling methods will help reclaim resources where possible. Thus, current scientific and technological efforts focus on reducing needed quantities, recycling, and developing resource substitution.

Water. Current research addresses the challenges of increasing water demand, quality of drinking water, wastewater treatment, and efficient irrigation systems. The desired technologies must include the entire water cycle together with the impact on the ecosystem and the consequences for economic growth and social justice. It is gratifying to see that in developing countries access to safe water grows faster than the population: in 1970 only 30% of the population had access to clean water, but in 1990 this figure had increased to 71%, and in 2004 84% could enjoy clean water.[29]

Food. Matching the energy, food, and water demand with limited natural resources and without permanently damaging the environment has been a major technological challenge worldwide. Many opportunities exist for the chemical sciences in all relevant efforts, including the increase of agricultural productivity, pest control, plant science, soil science, livestock and aquaculture, healthy food, food safety, process efficiency, affordability, and supply chain.

Health. The chemical sciences will play a central role in the development of new technologies related to aging, diagnostics, hygiene and infection, materials and prosthetics, drugs and therapies, and personalized medicine.[7] Some specific challenges include: enhancing the contribution of aging individuals to society while improving their quality of life; preventing, detecting, and treating chronic diseases, such as cancer, Alzheimer's, diabetes, dementia, obesity, arthritis, cardiovascular diseases, Parkinson's, and osteoporosis; establishing relevant biomarkers and sensitive analytical tools for early diagnosis of diseases; developing new materials for cost-effective, high-performance prosthetics, artificial organs, tissues, and eye lenses; improving drug delivery, etc.

Air. In the past decade the experience of the industrialized countries indicates that when the improvement of air quality becomes a major concern of the public, policymakers, and regulators, innovative solutions eventually emerge and are rapidly implemented. According to the European Pollutant Release and Transfer Register (E-PRTR) and the European Chemical Industry Council (CEFIC), European emissions of ammonia, sulfur oxides, and nitrogen oxides fell by 14% within the period of 2004–2009 whereas the overall industrial production has increased steadily. Various regulatory and voluntary organizations, such as the thematic strategy group on air pollution Clean Air For Europe (CAFE), the Industrial Emissions Directive (IED), the voluntary organization Responsible Care,[30] and many others, operate in concert to reduce the adverse effects of air pollutants on health and environment. It is likely that chemists and chemical engineers will keep developing long-term solutions to the problems of air quality.

Nevertheless, we need to remember that all of the current efforts follow research directions appropriate today. Based on past experience, new, revolutionary discoveries at the level of basic science may lead to unexpected reshuffling of our entire investment priorities and technological efforts. Great technology and smart products, which appear to us today as the culmination of human creativity, may find themselves tomorrow thrown in the junkyard of history, along with all their predecessors.

Conclusions

As a result of the population growth, humanity faces severe global problems, including limitations on energy, raw materials, food, water, health, and air, which seem daunting because they cannot be solved today on the basis of the current technologies. However, these challenges are likely to be met by yet unknown technologies. The future of humankind seems now brighter than ever for two main reasons: 1) the remarkably fast growth of human knowledge and 2) the unpredictability of science. Thomas Malthus and his disciples have ignored both.

Policy makers have forever been driven by the desire to solve major problems as quickly as possible. Unfortunately, scientific discoveries cannot be planned. It would be pointless for administrators to instruct scientists on what to do, simply because we have no idea where science is heading. Therefore, the best that can be done is to provide scientists with proper laboratories and support high-risk/high-gain research programs. A good example of this approach is the policy taken by the European Research Council (ERC) to support curiosity-driven, groundbreaking research programs led by individual scientists. Exploratory scientific activity will eventually result in surprising discoveries and enabling technologies.

Humankind will probably survive on this planet for many years to come, the above-listed problems will be solved, and chemistry will play a central role in any solution. Our real problems are not those listed, but rather the increasing gaps between the advanced societies and those who are left behind in the darkness of scientific and technological ignorance, in misconception, and pseudo-science. It is our responsibility as scientists to help closing these gaps, at least within our own communities.

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