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GUEST EDITORIAL

From digital technology to living machines

In the context of the extraordinary crisis that the world is experiencing with the COVID-19 pandemic, we are going to need a 'reset'. According to Noam Chomsky, we are facing the most dangerous moment in human history. It seems natural to assume that technology will have to drive the agenda. We wish that it would be driven by humanitarian concerns as well, rather than just technology, but unfortunately, as George Santayana famously said: 'Those who cannot remember the past are condemned to repeat it'. If there is one lesson from our pandemic experience in 2020, it is that while we have made amazing progress in responding to the crisis scientifically and technologically, as a society we seem condemned to repeat historical patterns of conspiracy theories, polarization and socially irresponsible behaviour.

The world today and the pace of technological change, as well as the scale of disruptions, suggest that advantages of the future can only be imagined with an understanding of the scientific and technological trajectories that have brought us to the present. The remarkable advances in technology, at an exponential scale, that we have witnessed over the last 100 years towards digital revolution and the second machine age, and how we are now poised to enter the age of living machines are the narratives of this write-up. But as Martin Heidegger (*The Question Concerning Technology and Other Essays*, translated by William Lovitt, Garland Publ., 1977, pp. 4–5) has warned us, we need to look beyond technology as a 'means to an end' and consider the 'essence' of technology which has dimensions, both instrumental (means) and anthropological (of human activity). To posit ends, and procure and utilize the means to them, is a human activity. And essence (or the noun 'Wesen' in German) 'does not simply mean what technology is, but it means, further, the way in which technology pursues its course, the way in which it endures'.

A century ago, physicists and engineers combined forces and symbiotically produced technologies such as telegraphs, telephones, radios, aircraft, radar, electromechanical calculators, power systems, and completed the agenda of the first machine age. The post-World War II era, the middle of the 20th century, saw the role again of physicists and mathematicians, fresh out of the war effort, looking for new frontiers and aiding in the birth of computers and digital hardware, along with the beginnings of molecular biology. The digital hardware was a little further along and was soon laying the foundations that would usher in the next revolution.

In 2016, at a conference in Bengaluru, Nandan Nilekani, remarked that 'apparently 2007 was when it all (population-scale infotech) began happening'. That remark by India's technology czar on inflection in technology deserved more investigation. In E. Brynjolfsson and A. McAfee (*The Second Machine Age*, Norton, 2014) also point out that all kinds of technology-driven 'miracles' are beginning to manifest in the last few years. Science fiction is turning into reality at a speed that is breathtaking.

The exponential Moore's law of semiconductor computing technology is clearly the manifest of the second machine age. To explain exponential growth, Brynjolfsson and McAfee use the example from the Indian 'Paal Payasam' fable about doubling rice grains on subsequent squares of the 64 square grid on a chessboard. When the chessboard is half covered, the 32nd square has roughly 4 billion grains. The steep effects of the exponential curve in the second half of the chessboard define the disruptive appearance of technological feats that seemed out of reach just a short while back.

Consider 1958, the date of registration of the first semiconductor company, as the start of Moore's law. Now doubling capabilities at a frequency of once every 18 months (Moore's law), we reach 2^{32} or the second half of the chessboard 48 years later, bringing us to 2006. Nilekani was right in speculating that 2007 was when 'it all began happening'. The impact we are seeing today of being on the 40th square of the chessboard with digital hardware is even more dazzling.

We are truly climbing at a steep incline towards instant communication, anthropomorphic and superior machine intelligence. Data scientists today have access to amazing scale in hardware at their beck and call. Software has been playing catch-up with hardware since the 1970s, when DARPA announced Project MAC to close the gap. So, if you are amazed by Alpha Go and Watson and Autonomous Vehicles, you haven't seen anything yet. Work, progress and prosperity with brilliant technologies is the promise of the second machine age.

The second machine age also warns us of the anthropological impact of unbridled power of digital machines, which will also create difficult social problems such as inequity in access to technology, the perverse use of technology to spread fake news and the ability of technology to influence traditional democracies. Cathy O'Neil calls these the 'weapons of math destruction', and Y. Harari (*Financial Times*, 26 August 2016) warns, 'once big data systems know me better than I know myself, authority will shift from humans to algorithms.' Recognizing the problems, societies are moving towards regulation of 'fair' use of technologies and protection of data privacy as a fundamental right.

Shifting our attention now to molecular biology, we note that its birth occurred in the immediate post-World War II period with the use of better instruments for measurement to help biologists get to the cell's hardware – the DNA, RNA and the protein building blocks. It led us to understand disease at a molecular scale. Early developments in the 1980s in biotechnology and the birth of biopharmaceuticals were essentially built on this understanding.

Meanwhile, another law of exponential technology has been evolving, that drives a different set of science fiction scenarios to reality: it is the law of genome sequencing – sometimes called Flatley's law, a biotechnology counterpart to Moore's law. The start date for genomics is 1984, when Sanger sequencing technology was commercialized. From 1984 to 2007, Moore and Sanger helped us get to efficiency improvement by a factor of about 2^{16}. After 2008, we have Balasubramanian and Klenerman's brilliant Solexa NGS (next generation sequencing) with massively parallel technology that was soon acquired by Illumina. So, the advances from 2008 to 2016 have got us to 2^{32}, and voilà, we are in the second half of the proverbial chessboard for genomics.

And this excitement about genome sequencing is just the tip of the proverbial iceberg. The next wave of the genomics revolution comes from our ability to write on genomes, i.e. to edit, or more accurately proofread, and modify them. This could have enormous impact, because potentially we will be able to do this for humans, plant genomes, animals, and microbes. Jennifer Doudna, the recent Nobel laureate and a pioneer in CRISPR technologies, calls this 'A crack in creation' (Doudna, J. A. and Sternberg, S. H., *A Crack in Creation: Gene Editing and the Unthinkable Power to Control Evolution*, 2017). Equity reports on genomic medicines estimate the total addressable market in human health at about twice India's national GDP.

Genomics, the software of biology, in combination with the advances in molecular biology, has positioned biology now to progress towards a quantified science that can open great synergies with engineering disciplines in materials research, micro- and nanotechnologies that can help biotechnology reach its long-standing promise in improving human health, food and energy security, and environmental sustainability. If so, this will certainly be the century of the life sciences and the foundation of an industry that would have a qualitatively different environmental footprint with unforeseen levels of automation with precision robotics.

S. Hockfield, the first woman and biologist to serve as MIT's President from 2004 to 2012, in her 2019 prize-winning book (*The Age of Living Machines: How Biology will Build the Next Technology Revolution*, 2019) describes how biology is going to create the next technology revolution. She concludes that her hope for a better future rests with as much confidence on the next generation as on the technologies themselves.

We do need to be alert even more about the impact of unbridled living machines. F. Fukuyama (*Our Posthuman Future: Consequences of the Biotechnology Revolution*, 2002) was troubled by the prospect of eugenics when he wrote in 2002 that biotechnology presents us with a special moral posthuman dilemma. The actions by the renegade scientist, He Jianqui at Shenzhen, China, in 2018 with gene edited and implanted embryos has reinforced this spectre. Even Doudna was haunted by a dream in which Adolf Hitler appeared, holding a pen and paper, requesting a copy of the CRISPR recipe.

The success of the Indian infotech industry in the latter part of the 20th century owes a great deal to the visionaries in the government in the 1960s and 1970s. The Department of Electronics, Government of India identified 'software led exports' as a segué for Indian export promotion in 1972 and provided help at the right time, and did not over-regulate the sector once it was off to the races. A marvellous example of directed public policy in technology.

The obvious question to ask is whether India has a strategy that can help us ride the steep advances in bioengineering to build a bioeconomy. What are the right levers to push this sector of Indian Biotechnology onto the world stage? The decisions we make today will make a difference.

P. Romer ('An interview with Paul Romer on Economic Growth', Featured Article, Library of Economics and Liberty, 5 November 2007) tells us that countries that take the lead in the 21st century will be the ones that implement innovation ecosystems that more effectively support the production of new ideas in the private sector. Economic growth occurs whenever people take resources and rearrange them in ways that make them more valuable. Possibilities do not merely add up; they multiply (Weitzman, M., *Quart. J. Econ.*, 1998, **113**(2), 331–360). An interesting approach is the idea of creating virtual marketplaces (e.g. Indigenous Diagnostics (InDx)) that can accelerate such rearrangements. Using the phraseology of bioengineering, recombinant growth has to be the focus of our national strategy.

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