deal with systems problems?' You cannot tackle a systems problem by just fiddling with one tiny part of the system. You need to look at the whole system and its interactions. We have been building on Tony's legacy; the Commission that I chaired for the Rockefeller Foundation is built very much on the legacy that he has left. So, certainly he is someone who will be remembered with great respect and affection, and his contributions will certainly endure.

What is your message for the young epidemiologist who wants to make a career in infectious disease and public health?

Well, my message is not just for the young epidemiologist or those in infectious diseases, or non-communicable diseases. My message is that we need to be more thoughtful and consider the impacts of our work from a systems perspective, because if we do not, then we may devise solutions which will work only for a short time. Unless we think about the long-term implications of what we are doing and how they fit into the necessary system changes, these successes will only be temporary or transient. So if we do not think about the system issues, then we can have unintended adverse consequences. For example, the French President Emmanuel Macron put forward a carbon tax to reduce GHG emission. Anyone who has looked into the literature knows that he did it the wrong way. It is not right to impose a tax on people, especially one which hits the poorest without preparing the ground carefully and redirecting the taxes back into the people's pockets or providing other tangible benefits. We may see such examples even in our health system. Sometimes we do things which appear beneficial to us, but in some ways they make us more vulnerable. For example, we can build a hospital which requires a lot of energy generated from fossil fuels, but that will have consequences for emissions, and costs. It may also have consequences for resilience, for example, when the electricity supply fails or when a building is damaged by an extreme climate event – as in the case of hospitals built on floodplains. Thus it is always better to think about the future and what the world is going to be like in the next 40–50 years from now. So my message would be to think in a systems way, even if you work on a specific problem. Try to conceptualize how things work and how they fit into the broader system and where it is possible to do so, collaborate with different disciplines so that you can better understand the whole context of what you are studying. There is no point in introducing a new intervention, for example, if people cannot accept it or it meets with resistance. We have to understand how to change behaviours, and how to change policies. We need to think widely about the implications of what we are doing, talk to our colleagues, engage in interdisciplinary presentations and interactions and learn from each other.

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OPINION

Are there limits to artificial intelligence?

Subhash Kak

Information technology has become the big driver of change in industry and society[1]. Robots have transformed manufacturing, and machines using artificial intelligence (AI) are increasingly replacing humans at tasks where learning and judgment are required. Just as brick-and-mortar stores appear unable to compete with online retailers, colleges and universities will have to innovate and transform or become obsolete. What this might do to the pursuit of science in the university is hard to fathom.

Some say that the current phase of automation will create new kinds of jobs that we cannot even imagine. They point to the automobile revolution over a hundred years ago, which people feared will destroy many trades of the day. The automobile revolution did create new kinds of jobs, but it did not turn out so great for the horse. The current revolution is replacing the thinking human and so its impact on society will be enormous. These machines would save us from workaday drudgery, but a life of no work and only play is unlikely to lead to individual or social well-being even with guaranteed minimum income[2]. The great English novelist Aldous Huxley foresaw many parts of this unfolding future in his *Brave New World*.

Science and consciousness

Is it possible that the machine of the future will be aware of itself and its surroundings? It might not only drive, cook, clean, do laundry, but also keep humans company when other people are not nearby. A group of computer scientists, neuroscientists, physicists and philosophers met this past year in several workshops across the US and UK to discuss these issues, and I would like to present my impressions of these meetings.

There was broad agreement that literally all cognitive capacities will eventually be emulated by machines. A minority believed that the phenomenon of consciousness, by which we mean awareness, will be beyond the reach of AI. Their argument was that cognitive capacities are computational but their assignment to the autobiographical self is a process that is associated with awareness and memories. This assignment occurs with consciousness as a singular phenomenon. Sentience is a complex dance between being and becoming, where the former is consciousness and the latter is the physical reality.

Another important viewpoint on consciousness comes from quantum theory, which is the deepest theory of physics. According to the orthodox Copenhagen interpretation, which was popular with the pioneers of quantum theory such as Niels Bohr, Werner Heisenberg and Erwin Schrödinger, consciousness and the physical world are complementary aspects of the same reality.

Since it takes consciousness as a given and no attempt is made to derive it from physics, the Copenhagen interpretation may be called the 'big-C' view of consciousness, where it is a thing that exists by itself – although it requires brains to become real. Many philosophers believe that the modern quantum physics views of consciousness have parallels in ancient philosophy and big-C is like the theory of mind in Vedanta – in which consciousness is the fundamental basis of reality, on par with the physical universe[3].

It should be acknowledged that the interaction between consciousness and matter leads to paradoxes – like that of Schrödinger's cat – which have remained unresolved after 80 years of debate. On the other hand, explorations of this interaction have opened the world to the field of quantum computing, with its many possibilities and challenges[4].

Biology presents a competing view of consciousness where it is seen as an emergent phenomenon, just as biology itself emerges from chemistry which, in turn, is based on physics. We call this less expansive concept of consciousness 'little-C'. It agrees with the neuroscientists' view that the processes of the mind are identical to states and processes of the brain, and it is also popular with many AI researchers.

Big-C and scientific discovery

There was divided opinion on whether consciousness is always a computational process. Some have argued that the creative moment is not at the end of a deliberate computation[5]. Thus, dreams or visions are supposed to have inspired Elias Howe's 1845 design of the modern sewing machine, and August Kekulé's discovery of the structure of benzene in 1862.

A dramatic piece of evidence in favour of big-C consciousness existing all on its own is the life of Srinivasa Ramanujan, who died in 1920 at the age of 32. His notebook[6], which was lost and forgotten for about 50 years and published only in 1988, contains several thousand formulas, without proof in different areas of mathematics, that were well ahead of their time[7]. Furthermore, the methods by which he found the formulas remain elusive. Ramanujan himself claimed that they were revealed to him by Goddess Nāmagiri while he was asleep[8].

The consideration of information (or entropy) in physical theory, which is commonly done in many branches of physics, implies an unstated postulation of consciousness. Information cannot be reduced to local operations by any reductionist programme. Consciousness cannot intervene in physical laws, but it can change the probabilities in the evolution of quantum processes. Thus in the quantum Zeno effect, which has been demonstrated in the laboratory, the act of observation can freeze the evolution of a quantum state without changing the dynamics, and this may be an explanation of how matter and mind interact[9].

If the phenomenon of consciousness is contingent on a recursive and self-organizing structure that constitutes the unity of an organism, as is true of the physical organization of the brain, then we know that current machines will come up short[10]. We do not yet know whether machines can be designed that will have such a structure, for we lack a mathematical theory of computation for adaptive, self-organizing components. Perhaps a case could be made that only biological machines can have such a basis, which opens up the possibility of engineering new biological structures that are conscious.

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