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Our travels through time:
envisioning historical waves of technological innovation

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Professor Lynn Conway's remarkable contributions to computer science and electrical engineering give particular weight to her perspective on future technological innovation. In a citation delivered before her lecture, Barry Shoop, President-Elect of the IEEE, described Professor Conway as a giant whose work had “fostered a revolution not only in her own profession but in countless other professions that have been able to flourish because of her innovations and discoveries.”

To set the stage, Professor Conway visualised some past waves of progress to help us understand how future innovations might develop. She quoted Winston Churchill: “The farther back you can look, the farther forward you are likely to see.”

The story began in the 15th Century, when advances in shipbuilding, navigation and map making triggered the Age of Discovery. The invention of the printing press meant adventurers could propagate news of what they had found much faster, dramatically enhancing exploration rates. Professor Conway asked: “Was that wave of innovation just the exponentiation of things – or was it the exponentiation of key clusters of innovative *ideas* in the minds of ever more people?”

In the mid-1700s, another tremendous wave of innovation – the Industrial Revolution – saw the mining and processing of coal and iron ore greatly amplified by steam power; a process which involved the propagation of the idea of the steam engine. Professor Conway noted that some of the resulting iron was used to make more steam engines and that this positive feedback fuelled an iterative expansion process, not only of things but also in ideas about how to use things.

The expansion of the rail network in the USA was accelerated by the rapid spread of telegraphy, beginning in the 1850s. This had an effect analogous to that of printing in the Age of Discovery, but at a different time scale. In the 1890s, as a result of the widespread harnessing of electricity, innovative technology clusters lurched out in new directions, including the invention of electric generators, meters, lights and telephones. Professor Conway wondered how many minds the ideas of Michael Faraday, James Clerk Maxwell, Heinrich Hertz and Charles Steinmetz passed through to make that happen. She observed: “The flow of ideas expands as a function of the increasing conductivity and bandwidth and the decreasing time delays in social communications.”

Innovations in integrated circuitry in the 1960s enabled transistors to be lithographically printed onto chips of silicon. In 1976, Gordon Moore observed that the number of transistors printable on a chip was doubling every two years – later dubbed Moore's Law – while Carver Mead further determined that there is no physical limit to prevent upwards of one million transistors being fitted onto a single chip. This observation prompted a push by research teams – including Professor Conway's at Xerox PARC – to work out how to design such complex chips.

The breakthrough was triggered by a cluster of abstract innovations, including a set of scalable VLSI (very-large-scale integration) chip-layout rules which enabled abstract chip designs to be digitally shrunk down. The driving idea, Professor Conway said, was that computers could use the new methods to design the chip sets for more powerful computers and, if more engineers and programmers repeated this on an expanding number of increasingly powerful computers, then the iterative expansion process could explosively generate ever more powerful digital systems. Professor Conway said that it is not just the ideas that count; it is how many heads those ideas rattle around within.

But there was a problem. Where would all the engineers and programmers come from? Professor Conway's solution began with a pioneering course at the Massachusetts Institute of Technology in 1978. In the first half of the course, students learned to design chips and in the second half they designed chips collaboratively and competitively, which were then printed by Hewlett Packard. The following year, the course was rolled out to students at 12 research universities across the USA, with their chip designs being remotely submitted over the Arpanet to a server at PARC before being printed.

Professor Conway observed that such techno–social dynamics triggered exponentiation in the evolution and diffusion of new VLSI design ideas. This was nurtured by a nested cluster of systems, while the new designers used their tools in new ways socially in the emerging Arpanet computer research community. In 1980, Professor Conway and Carver Mead produced the celebrated textbook *Introduction to VLSI Systems* and by 1982, their VLSI design course was being offered at 113 universities around the world, including Edinburgh University.

Professor Conway then turned her lecture 180 degrees to look into the future and glimpse another huge, incoming wave of innovation: “this one's the big one.” She observed that up until now, microsystems have been deeply embedded inside things such as smart phones and autos. “Folk just don't visualise the many ideas in motion behind effects such as the astonishing out-of-body experiences you can have right now by flying a Parrot Bebop using an Oculus Rift,” she said.

But this is about to change with efforts to create modular smartphones, Professor Conway predicted. These are set to popularise the concept of micro-hardware apps, tiny modular versions of currently-big things such as cameras, GPS units and inertial measurement systems, which can be ‘stuck together’ to configure customisable smartphones.

Such microsystems include all kinds of tiny, printed micro-electro-mechanical (MEMS) chips which enable the creation of a vast array of transducers and sensors which could, for instance, be used in nanodrones with HD cameras, auto-following and swarming capabilities. Professor Conway insisted that such things are not frivolous playthings – they metaphorically illuminate a vast frontier for human empowerment and application. For instance, the bed-ridden patient in a lengthy-stay hospital could actively explore the world beyond her window using her smartphone to control a drone. Alternatively, imagine joining your friends on group drone tours of remote and remarkable places.

Instead of printing a billion transistors onto a single large smartphone chip, Professor Conway said we could print a million transistors on 1,000 tiny, but powerful, chips. You can embed lots of stuff, including MEMS micro mechanisms, into almost everything and then enable clusters of tiny chips to interactively control lots of macro-scale systems such as robots and drones. Professor Conway said that this embedded microsystems revolution is already getting on a big head of steam: “There's a huge amount of entrepreneurial and innovative activity going on in many sectors.”

One key cluster is 3D printing. Once perfected, design files can be shared and marketed to other 3D printer users who can just print the object out. Professor Conway suggested that 3D printers could be used to print better 3D printers. Just as when some of the iron was recursively fed back to make more steam engines, providing such positive feedback provides gain in the emerging 3D printing technology ecosystem, which then starts to grow exponentially.

So where are all the young innovators going to come from, Professor Conway asked? She said there is a huge wave running through engineering of technology-empowered, socially-exploratory methods for providing better education. Many students have had experience at Lego camps, maker fairs and robot competitions, while they can also gain ongoing knowledge as needed from online sources. She observed that there are also new techno-social methods such as collaborative learning, crowd sourcing and crowd funding, which enable more people, from engaged users to innovators to makers, to scale up their levels of participation in these processes.

Professor Conway said that instead of making ever bigger things that go further and faster, we could invert our spherical perspective 180 degrees and look inward to the inner spaces of the micro/bio/nano/pico world. She said that as we explore how to make, share and exploit the vast exponentiations of ever tinier, ever more empowering micro/bio/nano things, we could start to do more and more with less and less.

Indeed, it has already begun. Before long, adventurers everywhere are going to be surfing on this wave of innovation. As people begin to grasp the possibilities, Professor Conway said there will be many exponentiations. A lot of it is going from ideas to working prototypes, with processes that involve codifying and teaching, learning and practice, collaboration and competition. Many such processes are running in parallel and cross-fertilising, all intermediated by social media.

Escalating techno–social change will also greatly challenge existing cultural patterns. How can we ever adjust and keep up, Professor Conway asked? She suggested pondering the words of philosopher Eric Hoffer: “In a world of change, the learners shall inherit the Earth, while the learned shall find themselves perfectly suited for a world that no longer exists.” She added her own perspective by way of compensation: “As the rate of techno-social change increases, we'll all live further into the unfolding social future than we ever dared dream.” It will be almost like living forever, she said. But Professor Conway introduced a note of caution – avoid being distracted by all the rapidly emerging things – technology alone will not change the world.

Professor Conway predicted that the evolution of effective social leadership, amid the escalating generation and diffusion of ever better ideas of how to make and use things, will trigger huge re-alignments in political economy. She said that this incoming wave of innovation has the potential to:

- sustainably provide ever-increasing infrastructural functionality and life empowerment per person;
- consume ever-decreasing energy and material resources per person;
- begin the reining-in of the unsustainable overuse of planet Earth; and
- open an unprecedented exploration of the greatest of frontiers – the frontier of what is possible.

Professor Conway concluded with a personal perspective: “If you want to change the future, start living as if you're already there.”

Questions and Answers

Q: Are we on the way to artificial intelligence, of machines having their own ideas?

A: Professor Conway said the terminology is challenging. She said things tend to be called artificial intelligence when in the speculative domain but when achieved they seem less so. She said it seems likely that we will have increasingly empowered personal assistants, which will help people do many things with a degree of learning to do all sorts of low-level things. But at some point people will start talking about artificial consciousness.

Q: How can we reconcile the grand vision outlined in Professor Conway's talk with the growth of religious fundamentalism?

A: There are probably instabilities that will appear as more people grasp what's going on and others resist seeing the world in a more social way. It's a question of recognising the reality of our own non-singularity, being carriers of memetic structures and propagating memes. There will be things which cause more problems for the thinking of people with fundamentalist religious memetic structures.

Q: What is pushing progress in this area fastest – pure science or market-driven science?

A: I think we are obsessed with economic models. I sense the deep driver being an urge to explore, an urge to push out boundaries, an urge to experience an opportunity space that's appearing right in front of us. As more people push out boundaries, creatively, imaginatively, intellectually, it will be like a new Renaissance.

Q: A famous historian said that the reason why the Greeks were so productive intellectually is that they didn't have so much grass to cut. I observe a lot of people not thinking about very much but doing – and doing trivial things. I almost see this as a progression away from the Greeks.

A: A lot of people are caught up in social media, almost obsessed with it. That's part of the transient process of people being the early adopters, a new generational thing. But while you might observe things being done that may look trivial, you may not be aware of the learning experience they are having; you may not be aware of the new, vibrant social group phenomena occurring. They are exploring this space and learning the early moves so they are going to be ready for the next wave of stuff that comes in.

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