Personal reflections on fifty years of digital revolution

By David Potter

Nearly fifty years ago as a foreign student at Cambridge I wrote a weekly sea-mail letter to my mother in Africa. Many weeks afterwards a reply came. Later as a postgraduate, research required long hours of copying papers in old libraries. And my thesis was written by long-hand and later typewriter. Written information flowed at the pace of physical transport. In South Africa there was no television and a mere two or three state-controlled radio stations. Opinion and news were furnished by a few national newspapers.

Fifty years on, information and ideas travel across the globe in milliseconds. We are linked by the net, perhaps the most transforming infrastructure created by humans. Much economic activity including communications, service functions, logistics and manufacturing has been automated by digital technology. Great libraries of accessible, structured data and knowledge are immediately available. Almost every device and machine whether in the home or office has been automated with new human interfaces. The price of goods across the world has declined progressively over the last twenty years. We are swamped by news, instant opinion, images and public relations that cater to the popular view.

This is the information revolution. It has transformed the world in my adult life. In its economic, social and political impact it stands in the modern era alongside the agrarian and industrial revolutions as the third great transformation wrought by science and technology.

The change has occurred as in a long train journey from coast through mountains to the Highveld. Over short periods, the scenery through the carriage window looks much the same. It changes only slowly and incrementally in time. It is the sum of many small transitions that suddenly brings a quite different view. In the advance of technology, communications and computers, so many dramatic and progressive changes have been implemented that only by stepping back can we see how the landscape of our lives has been transformed. That will be the job of historians to write. My life as academic, entrepreneur and policy contributor has been lived in the locus of the digital revolution and this essay reflects a personal perspective through that journey. But my wider goal here is to illustrate the scale of change in how we conduct our working and social lives and in how our economy and society have altered.

How did this happen? What was the science? How was the technology created? And how was economic value delivered commercially? How have these changes affected the way we think, the public discourse and the relationships between social classes on the one hand, or nations on the other?

THE SCIENCE

Politicians and policy makers make little distinction between science and technology. A widespread policy approach is to feed money into the science hopper in the belief that technology and new enterprise will flow out the other side. There is nothing linear in the path from scientific discovery to economic benefit. That path is osmotic, empirical and uncharted. The South African-born President of The Royal Society, Aaron Klug (the surname means 'clever' in Yiddish), expressed it well in his valedictory address to The Society in 2001. Progress in science is driven by individual curiosity. We humour and encourage curiosity in children. For most adults however the need is to work co-operatively in delivering the many demands of our society such as the provision of sustenance, clothing, entertainment, housing or healthcare. Good science cannot deliver known goals, but trying to answer good questions, though often fruitless, sometimes opens new understanding. The scientific path is unknown; technology in contrast is goal-oriented. The information revolution is the clearest example of this.

More than two thousand years ago, Greek philosophers had asked whether matter was infinitely divisible. By the end of the 19th century classical physics showed that there was a finite limit; compounds could be separated into elements and the smallest part of an element was called an atom (from the Greek, meaning un-cuttable). But in 1899 J. J. Thompson, while studying cathode rays, discovered a much smaller negatively charged particle which he called an electron. Atoms could be stripped of an electron leaving a positively charged atom. Ernest Rutherford, Professor of Physics at Manchester University, asked a wonderful question. Were atoms dense like billiard balls or did they have structure? In a brilliantly conceived experiment he examined the scattering of electron-stripped helium atoms through a thin gold foil. Rutherford's experiment reported in 1911 showed that the atoms of gold had a heavy positively charged core surrounded by negatively charged electrons — a planetary model of the atom.

The Rutherford observations raised a further major problem. According to the classical physics of the time, a small negatively charged electron orbiting a heavy positive nucleus should radiate away its energy and collapse into the nucleus. Earlier in 1899, Max Planck had suggested that not only were atoms indivisible, but the transfer of energy was lumpy or quantised at the atomic level. In 1913, Niels Bohr, following Planck and Rutherford, suggested that if there were certain quantised, or discrete, allowable, energy levels of the electron in the atom, energy could not be released from the electron and a stable planetary-like atom could exist. This 'Rutherford Bohr' model marked the start of quantum physics and our early understanding of the structure of atoms. By the 1920s, a proper axiomatic formulation of the subject and theory had been developed by the German theoreticians, Schrodinger and Heisenberg.

As science began to understand the structure of atoms with its new quantum theory, thought turned, inter alia, to the structure of molecules and to solid matter. The first of these fields led eventually to biochemistry, the genome and our developing understanding of life and micro-physiology. The second led to our understanding of the behaviour and properties of solids, conductors and semi-conductors and eventually created great new technologies.

The understanding of both the structure of molecules and solids were advanced by the discovery of X-ray crystallography. X-rays are part of the electromagnetic spectrum with wavelengths that are typically similar in scale to the separation of atoms in molecules or solids. A beam of X-rays targeted at a crystal will therefore interfere co-operatively with a regular lattice of atoms in a crystal. This phenomenon was observed by Sir William Bragg and Bragg's law of X-ray diffraction was published in 1912 with his son, Sir William Lawrence Bragg. Diffraction showed that solid matter was structured in regular lattices or arrays of atoms.

The new understanding of crystals and the electronic structure of atoms began to explain the behaviour of solids. What we called metals were solids made of atoms that had outer loosely-tied electrons. These 'nearly-free electrons' could move easily within the lattice providing conduction. In quantum terms, 'free electrons' were nearly unbounded across the crystal and therefore formed a near continuous band of energies. In contrast the widely separated energy levels of the deeper electrons in atoms or those of insulators tied electrons locally and disallowed conduction.

Felix Bloch, a student of Heisenberg used the new quantum mechanics to establish 'the band theory of metals'. Together with Enrico Fermi and others the band theory of conduction provided a beautiful explanation for the existence of insulators, conductors and their characteristics. This was science in all its majesty answering the question why.

THE TECHNOLOGY

1931: The year of Stuart's birth; the year that A. H. Wilson first published a paper on the possibility of semi-conductors. Wilson proposed that the doping of an insulator crystal such as silicon or germanium with a small even distribution of metallic atoms with nearly free electrons in their outer band would allow properties of 'semi-conduction' in the resulting crystal. Semi-conductors could be created by a small excess of electrons, or by the opposite effect of a sparsity of negatively charged ions that permitted 'holes' equally capable of transporting charge and energy. These were two different types of semiconductors called 'p' and 'n'. The development of digital electronics moved from the laboratories of universities to those of commercial firms. Foremost among these were the Bell Laboratories of the giant telephone company AT&T, Texas Instruments and Motorola, the wireless radio company. The possibility of semiconductors stimulated commercial interest through the idea of replacing large and unwieldy thermionic valves with small semiconductor valves or transistors. In 1953, the Bell Laboratories created the first transistor.

The beauty of the transistor was its small scale, ruggedness, low power and potentially very low cost. But more importantly, multiple transistors could be engineered within single crystals to create integrated logic circuits. Over subsequent decades, solid state engineers learnt how to fabricate larger and larger circuits on smaller and smaller scales that provided sophisticated memory and logic circuits.

The capital cost of fabricating logic and memory circuits was large and commercial benefit was unclear. When we examine the path from science through technology to economic benefit, we may often observe that a critical barrier is reached. Markets evolve empirically; but if the cost of the first commercial steps is excessive, how is a virtuous market cycle started? Some large external factor or agent must drive the necessary expenditure. And in the history of the digital revolution, that agency was the United States Department of Defence. This was in the era of what Eisenhower referred to as the 'military industrial complex'. The United States Department of Defence had particular interest in computer-controlled missiles for which semi-conductor circuits were essential. The rich funding of military interest drove the development of the new technology in the United States. America got its guidance system for missiles; but more serendipitously it came to dominate the young semi-conductor industry that grew to be a giant.

The first dedicated semi-conductor company was Fairchild. With growing commercial application, Fairchild prospered and spawned many new semiconductor companies, the most famous of which was Intel. Gordon Moore an alumnus of Fairchild and one of the founders of Intel identified the opportunity. He observed that semiconductors had the potential to double in size and halve in cost every eighteen months for decades ahead. This meant capacity would multiply one million times if progress continued for thirty years. The extraordinary new technology had the potential to change the world and it did. We shall see the effect of one million again and again in the following evolution of the technology. Has there even been a technology that multiplied capacities a million times in a few decades?

The technology of solid state engineering that derived from the new quantum physics was not constrained to integrated circuits, logic devices and memory. A great range of applications evolved including the solid state laser, the fibre optic cable, light emitting diodes, liquid crystal displays and rotating memory magnetic and optical disk storage. These technologies had the potential to transform communications, bandwidth, memory-storage and display technology.

A million times expansion of capacity: as the engineering pursued the possibilities of Moore's Law, the sheer scale of multiplication has been breathtaking. In 1980, a single memory circuit could support eight thousand bytes or characters of information. Today an equivalent memory circuit can store sixteen billion characters of information in a smaller package and with lower power. That is a multiplication in capacity of two million times in the space of thirty years close to Moore's prediction. Similar scales of capacity expansion have occurred in displays for television and computer screens and in the bandwidth of communications. And equally with the expansion of capacity, economic benefit through market forces has driven larger and larger volumes at lower and lower cost. The result is the ubiquity of the new technology.

Application

While the science was incubated through curiosity, the technology evolved initially at the intersection of government and companies engaged in the military industrial complex. The science was created in Europe; the technology in the United States. The earliest applications were missile guidance systems and military field communications (the forerunner of the cell-phone) in the United States funded by the arms race during the cold war. Human advances often seem empirical in their genesis. It is a wry observation that happily to date, nuclear missiles have never been deployed. But their creation spawned the early technology that drove the digital world. This is an example, common in history, of the osmotic, empirical and Darwinian evolution of technology from science. The first applications in wider commercial markets were the transistor radio and calculator.

It was the creation of the microprocessor in the early 70s that began to spawn ever-widening utility. In Albuquerque a kit microcomputer was launched called the "Aim" and it attracted Harvard drop-outs, Bill Gates and Paul Allen, to New Mexico to implement a programming language called Basic and found Microsoft. A family of microcomputers began to evolve with a common microprocessor, the 8080, and a common operating system created by a small company called Digital Research. In contrast Motorola produced a microprocessor called the 6800, and later the 6502, chosen by Steve Jobs and Steve Wozniak in developing the Apple II. These early products from funky new companies sold to hobbyists, software specialists and eventually consumers and small businesses. At this new frontier only radical visionaries engaged. A senior executive in the mainframe industry of the time said to me: "Given your academic credentials, what are you doing playing with these toys?" Since IBM was the standard in commercial computers, the introduction of the PC using Intel and Microsoft standards sanctified the microcomputer for business everywhere. In less than a decade, the office across the world was transformed with word-processor, spreadsheet, database, record-keeping and accountancy software. Belatedly IBM recognised the threat to its traditional main-frame and minicomputer businesses. Conventional thinking among the 'suits' of IBM let the new technology slip to others and the standards belonged to the visionaries. Within eight years, IBM was in great difficulty and had to reinvent itself as a services company.

The benefit of computers in the office was multiplied by linking them through local area networks. Work, information and databases could all be shared through the office network. But what if these networks could be shared remotely across different offices? Funded by military spending at the Advanced Research Projects Agency (ARPA), computer scientists, J. C. R. Licklider, Ivan Sutherland and Bob Taylor devised a radical new approach to a network that used packets of data like letters in the post to facilitate the robust requirements of extensive wide area networks. The first implementation was in 1969.

They called it Arpanet; it used standard protocols and was structured like a spider's web with multiple servers that could deal with the failure of parts, while the whole continued. From an early stage scientists began to use this Arpanet infrastructure to communicate and later the commercial world began to roll out the same standard. The Internet was born. The first application was email and soon financial and commercial databases were being accessed in time critical missions.

The World Wide Web overlaid on the Internet was devised by Timothy Berners-Lee in 1991 at CERN (an institute for collaboration on high energy physics). It expanded the Internet beyond communications to create accessible libraries of knowledge in every field of interest.

In parallel with the transformation of the office and the home, digital technology was to change our mobile lives. Early in the microcomputer evolution, portable computers were created and Psion introduced the first personal digital assistant and palm-top computer in 1984. At the same time, with its experience in military field communications, Motorola began to market car-phones that could maintain connection while moving through a network of wireless cells. As digital solid-state engineering worked its magic on size, cost and power, the car-phone and the PDA merged and created the largest technology market in the world that brought four billion people in touch with each other.

The digital solid-state engineering of the last sixty years has penetrated almost every aspect of life. Most importantly it automated not just the office but the factory. Manufacturing processes were automated by high speed machines that were microprocessor and software controlled and could be applied to almost any manufactured goods: cars, computers, cell-phones, clothing, books, plates, bottles, pharmaceuticals. The labour of man had been reduced ultimately to tending the machines that manufacture our needs. The cost of goods has plummeted over the last twenty years due to the automation of manufacture and less to the addition of new sources of cheap labour.

When I write to my children today in another continent, I send my letter by email and they might access it within seconds or minutes. This is a new universe compared to communications with my mother nearly fifty years ago. And so it is in all forms of communication and media. The worlds of newspapers, magazines, television and radio are transformed with multiple media and, because of falling cost, multiple channels. Everyone has immediate access to news, opinion and spectacle.

Supporting the scale of this communication explosion is the fibre optic cable, again fashioned out of the new solid-state engineering. From the British Navy laying telegraph cables across the world in the nineteenth century, the bandwidth afforded by today's fibre-optic network encompassing the world is billion-folds larger.

And in this wide view of the effect of the digital transformation it is worth ending on the most recent impact on our lives: the engineering marvel of the giant Liquid Crystal Display television screens sold today. With diligent patience over thirty years, Japanese and Korean engineers and companies learnt how to manufacture forty-inch screens with ten million multiplexed components, working in perfect harmony and meeting the requirements of a mass market. Again a million times expansion over thirty years. There is more to come.

THE ECONOMIC IMPACT

It is no exaggeration to say that going digital has transformed all the different spaces of our lives. To the present time, industry production figures suggest that some thirty-five billion microprocessors are now operating in the world. Rather more than half of these are embedded as controllers in almost every device we rely on. Today's motor car has typically thirty or more. So do the fire and security systems that protect us. We pay for products and services with credit cards interrogated by microprocessor terminals. Washing machines, ovens, traffic lights and laser scanners are all controlled by digital technology. In health care, microprocessor-driven tomography has expanded medical diagnostics dramatically over the last twenty years.

But what has been the wider effect on economy, on our social compacts and on the political culture?

For mankind as a whole, a key transformation has been the roll-out of personal communications, courtesy of the cell-phone over the last twenty years. Today it is not only the developed world that has a personal phone, but most of the world. Cell-phones simply allowed telephone access to rural areas, villages and towns that had never had the benefit of land-lines and exchanges. A country like South Africa now has a penetration of 70% of the population. There are some four billion cell-phones in the world providing direct contact for most people irrespective of rich or poor circumstance. The benefit in personal, social and commercial terms is immense.

Satellite TV, the Internet and Web add public information to personal communications. And universal access to shared media contributes elements of a global culture in sport, film, products, services and perhaps shared values.

The effect on the structure of the world economy is less transparent but more profound. This is true of financial markets, manufacturing, engineering, ordering, logistics, retailing and service functions. Economic history identifies increasing human specialisation as a core driver of progress. Alternatively it might be that technology provides greater productivity that in turn frees humans to specialise further. Such specialisations require the linkage of trade, communications and co-operation between the groups that create a value chain. The early hunter who stayed in the village to work leather and provide clothing is an example. But he would need to barter or trade his goods in return for food. Today's world of business is built on great specialisations and long, complex value chains. Going digital has turned the value chain from local to global.

Designed in California; made in China, 21st century businesses segment their activities in different regions, countries or provinces; each link is located wherever comparative advantage is optimised. Call centres are located in unemployed north Scotland, Bangalore or South Africa. Manufacturing is sited at the fulcrum of component specialisations.

Research is located near universities and educated workforces. This is true of the large or small company so that the corporation is trans-national and no longer belongs to a particular country. Nations must compete to attract activity on the basis of tax, investment support, the provision of infrastructure or an educated populace.

The global value chain is enabled by communications, band-width and the automation of information in the business. Digital technology has allowed businesses to structure, capture, store and access the organisation's information covering the management of inventory, order-capture and fulfilment, global logistics in the transport of goods, and automated machine-based manufacturing.

Going digital has changed manufacturing more than any other activity. We do not see the process as we see cell-phones or credit card payments, but the effects on productivity and the falling cost of goods are everywhere. The great assembly lines, immortalised by Charlie Chaplin's *Modern Times*, are gone. People have been replaced in the repetitive tasks of mass manufacture by programmable microprocessor-controlled machines that can integrate a hundred components in thirty seconds. These advances are seen in the macro-economic data of the last twenty years. Over much of the world and particularly in the large consuming developed-countries, the progressive deflation in the price of goods has been a major feature. It is not the policies of central bankers that have driven this deflation. It is partly the expansion of low-cost labour with the new value-chains that business can use, but beyond any of these it is the automation of manufacture. The first industrial revolution was driven by power and the machine. The second has been driven by digital automation. As a side note, inflation in North America and Europe has been low and stable for twenty years. In these countries about half of the consumption basket is filled with goods and about half with services. The inflation index has been low with inflation of services high and goods negative, allowing a temporary, halcyon period for these countries.

Finally we cannot ignore the effect on the financial world and the impact for good or ill on the world economy. Financial intermediation and capital markets are driven by information and they were among the first to begin to use digital technology. Today the sheer volume and speed of transactions in both real and derivative markets is awesome. Hundreds of trillions of dollars are transacted through the foreign exchange markets each year. And there has been a multiplication of instruments of Byzantine complexity through securitisation and forward contracts. The economy of products and services deals with present value but capital markets deal with future value in tomorrow's unknown virtual world. We see the lunacy of the talking heads in front of the flashing tickers of financial markets, shown on Bloomberg or CNBC and wonder at its benefit. The complexity created by this world outstripped the capacity of economists, governments and regulators to comprehend it. While there were wide benefits in facilitating the expansion of credit and finance, the age-old problem of human herding and greed supercharged by the digital capacity of financial markets led to the Great Financial Crash in 2007-09.

Going digital has wrought great benefit across the world by facilitating the global economy. This has brought increasing millions of the people of the world into the modern economy and shared economic benefit across growing numbers of previously dispossessed countries. Nowhere is this truer than in China and Asia. It is an irony that while the new emerging world focuses on real economic activity in goods and services, the Anglosphere of America and Britain particularly has eschewed manufacturing and focused on the virtual world of capital markets. The result has been the North Atlantic Crash while economic power shifts irreversibly to Asia.

Media, social and political impact

Economic change inevitably changes the social and political context. Overlaid, is the impact of the rapidly changing world of media. Newspapers and broadcast are fundamentally information purveyors and both have seen the automation of their production and distribution reinvented by the new technology. The cost of production of newspapers fell as the manufacture of the daily newspaper and its distribution were automated. Editorial condensed as the key cost. Broadcast went digital and added new forms of delivery such as multiple satellite channels. Radio channels proliferated and the Internet provided a new giant real-time competitor. Suppliers of media and with it news, opinion and entertainment have experienced an unprecedented expansion of competition. They respond today by pursuing populism and ephemera. The moving image has replaced the written word with a reduction in the attention span. The result is a celebratory culture, footballers attracting extraordinary cash flows, and politicians making policy in the public gaze of their electors.

More generally the portability of digital information destroys its security for the individual, for private organisations and for governments. Privacy is dead. Governments monitor internet and cell-phone traffic. Whistleblowers with a small memory stick or communications can transfer state secrets to public websites or bank customer data to newspapers and the state. Security cameras watch our moves in all parts of the city.

The Internet and social media provide new conversations among large interest groups, fomenting political action through strikes or revolutions. Dispossessed people living under autocratic rule see daily the basic human rights and conditions enjoyed by other more fortunate nations and classes. We have seen this in Tunisia, Egypt, and Libya. We have seen the corruption of politicians exposed, and authorities embarrassed through agents such as Wikileaks.

The consequence is a new narrative for the conduct of politics. To those of an ultra liberal mind, there is only virtue in the freeing of so much information, public and private. But does the new narrative exclude private and considered debate for cabinets and boardrooms? Do the demands of continuous popular gaze force politicians to pursue the lowest common denominator and eschew careful thought and policy making?

In contrast, social networks drive and facilitate new communities. The Web gives instant access to great libraries of information. Research and learning has been transformed with instant access, great capacity, browsing and search facilities undreamt of twenty years ago. Going digital has changed the world.

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