



Digital computing, modelling and simulation

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Digital computing, modelling and simulation

An examination of recent advances in computing is central to understanding the last seven decades of scientific and technical progress. Improvements in speed and processing since the 1940s have allowed computer scientists to solve huge numbers of equations very rapidly and build increasingly detailed simulations. These improvements and accompanying cost reductions have exposed fields of study previously opaque to experiment and direct observation, like climate modelling and high-energy physics, and have revolutionised other disciplines, like astronomy, ecology, engineering, and economics. Digital modelling and simulation has become a critical general purpose tool, and its multiplicative effects across all fields of industry and enquiry will ensure its importance and influence into the future.

Overview

- The rise of computational modelling and simulation illuminates some important themes in the history of technology.
- While modelling has been an integral part of scientific enquiry since classical antiquity, the history of digital modelling and simulation tracks the development of the electronic programmable computer, and begins in the United States during the Second World War.
- Unanticipated even by its creators, rapid adoption of the digital computer by business during the 1950s and 1960s helped transform the computer industry. In turn computers transformed business processes, illustrating the importance of serendipity, adoption, adaptation, and appropriation in the history of technology.
- Understanding the potential of the digital computer as a tool for complex computation and modelling, in the 1950s military and other government funders helped create a new standard for cross-sector collaboration in computer innovation, involving public and private sector and universities.
- In Australia, the Council of Scientific and Industrial Research (now CSIRO) built CSIRAC, the world's fourth digital computer with the capacity to store programs, in 1949.
- CSIRAC briefly placed Australia close to the forefront of contemporary global computer research, and helped transform a number of fields of research and industry.
- As a general purpose conceptual tool, computer modelling and simulation in some form is now almost ubiquitous in scientific research, engineering, manufacturing, and business, and is a critical constituent of the wider data economy.
- During the 1960s major technical changes introduced solid state transistor technologies which replaced the cumbersome, larger and more physically fragile vacuum tube technology. This breakthrough in hardware precipitated rapid progress in computer processing speed and storage, allowing associated improvements in calculation, modelling and simulation.
- Since 1965, Moore's Law has effectively described the exponential reduction in transistor size over time. The semiconductor industry uses Moore's Law for long-term planning and for research and development targets.
- Complex modelling and simulation continues to be closely associated with the advances in chip technology predicted by Moore's Law, in particular high-performance computing and the disciplines which rely on it (such as theoretical physics and astronomy); but for many fields of research, other intellectual and technological trends in the history of computing have partly decoupled improvements in modelling from raw computer power.
- Computer simulations are part of the construction and validation of scientific knowledge. They are often the only access we have to explanations for phenomena which are large and complex, or for which data are scarce. Therefore researchers and policy makers need mechanisms to evaluate the dependability of data arising from simulations which inform government policy.
- The history of the digital computer, and with it, computational modelling, can offer insight into technology adoption and adaptation, the relationship between science and technology, the social and economic impacts of emerging technologies, the role of serendipity, and the roles of government and industry.

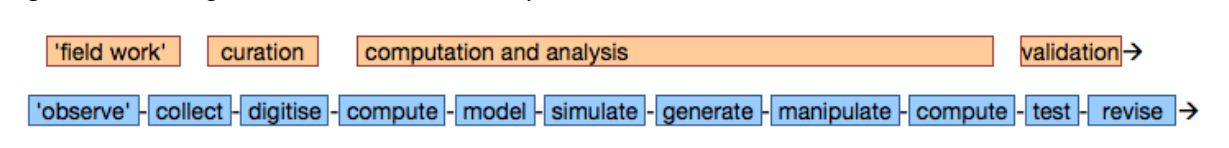
Digital computing consists of a set of technologies which underpin computational modelling and simulation, among the most pervasive and transformative scientific tools of the last 50 years. The histories of digital computing in the late 20th century provides insight into general processes of technology evolution, adoption and adaptation, and the relationship with prediction and planning. The past and current social and economic impacts of these transformative innovations may shed light on potential future roles for public sector organisations, policy makers, regulators and industry in anticipating and dealing with emerging technologies. This paper reflects on the entangled histories of digital computing, computer modelling and simulation, considered as a single innovation, and the influence of this technology on virtually all fields of industry and enquiry over the last 50 years. It is a powerful, near-ubiquitous, but nearly invisible general purpose conceptual tool.

A mathematical model is a simplified or idealised description or representation of a system, structure, or process (Table 1). To simulate a system is to execute or ‘run’ a model of that system: models and simulations are used to improve understanding of large and complex problems (Banks, 2009).

The first digital programmable computers were built to perform complicated mathematical calculations rapidly. Their successors have improved by several orders of magnitude the capacity of researchers to conduct the complicated and repeatable calculations needed to model and simulate large and complex systems. Since the 1950s, computer simulations have become a critical tool for understanding, in fields as diverse as astrophysics, meteorology, ballistics, economics, demography, epidemiology and electrical engineering – indeed, in any fields dealing with phenomena which cannot easily be studied in their entirety, transforming science, manufacturing, fabrication, characterisation, and public policy, as well as leisure and domestic life.

Computer modelling is also a central component of the global data system. The data amassed from many decades of observation, as well as data outputs from simulations of complex phenomena, have increased enormously with the development of computers capable of building detailed simulations and solving huge numbers of equations very rapidly. The resulting data-rich environment has fuelled increasingly data-intensive scientific and industrial applications (Figures 1, 4) (Douglas, 2015).

Figure 1. Modelling and simulation in the data system



The paper begins by considering the significance of the history of digital computation and modelling to themes in the broader history of technology. It examines the mutual entanglement of computation and modelling since the rise of the digital programmable computer. It explains what a model is, how a computer allows a modeller to understand complex systems in greater detail than pen-and-paper modelling, and the intellectual and mechanical precursors to digital computers and computer models. It looks at the practical limits and enablers of computer modelling and simulation. Digital computing, computer modelling and simulation is arguably the most influential general purpose technology to arise in the last half century for its effects in combination with other technologies including other information and communications technology (ICT).

Understanding how people have designed and managed new technologies in the past helps policy makers, industries, and innovators to understand current patterns of innovation, use, and adoption, and may help them design for the future. The story of digital computing, modelling and simulation is an example of a complex interaction of technology systems, scientific practice, business and industry

innovation, government policy, funding models, and design. As such, it can help illuminate broader questions about the:

- **boundaries of technology, science, and infrastructure**, which are often overlapping, complex, and interdependent. For example:
 - Digital programmable computers are at the same time scientific and technological artefacts, sites for the performance of research and technology, and indispensable research and business infrastructure; and
 - Computational modelling and simulation performed on digital computers are critical components of technological systems, as well as a fundamental research tool.
- **drivers for innovation and adoption**
 - In common with many other technology markets, drivers for innovation and adoption of digital computers, modelling and simulation include productivity effects (presumed or real), markets, patterns of use, cross-sector adaptation and appropriation, and financial and regulatory innovation.
- **roles and risk in science and technology**, for example, the different responsibilities and requirements of modellers/scientists, policymakers in government and industry, and regulators
- **trust, understanding, and communication**, for example, the trade-off between predictive performance and explanatory power of a simulation
- **workforce, education, and skills needs and effects.**

Digital computing: a general purpose technology that shaped the late 20th century

The history of the rise of electronic, programmable, general purpose computers in the latter half of the 20th century, and the parallel rise of computational modelling and simulation, helps clarify some recurring themes in the history of science and technology, which in turn illuminate the *Technology and Australia's Future* project questions. These major themes include the relationship between science, engineering, and technology; the extent to which technological innovation creates or responds to demand; patterns of technology transfer, adaptation to and adoption of technologies within and between cultures; the role of economics in innovation; and the roles of government and industry in fostering and directing technological innovation and development (Mahoney, 1988).¹ Modern electronic information technologies pervade and are shaped by 21st century security, cultural, democratic, social, and economic systems. As historian of technology Michael Mahoney wrote as long ago as 1988, 'The shaping of scientific concepts and the pursuit of scientific inquiry ... depend on the state of computer technology'. This dependence is reciprocal via organising and coordinating effects, if, with Mahoney, we consider science and technologies as 'interactive constituents of systems' whereby a breakthrough – or a breakdown – in one part of the system may serendipitously produce new opportunities in other parts of the system, 'or even force a reorganization of the system itself'.

The history of the invention and development of the microchip, for instance, parallels breakthroughs in design, speed and power in digital computation, accompanying improvements in programming, modelling and simulation, and the invention of software. The latter 20th century was unavoidably shaped by, and shaped, the challenges and opportunities of digital computing. Computers are embedded in any field of research that requires large volumes of data, high-speed calculation, or computationally-intensive algorithms (Mahoney, 1988).

¹ See also *Technology and Australia's future*, project research questions, <http://technologyforaustralia.org/about/>.

Box 1. Science, technology and change

'With the advent of everyday use of elaborate calculations, speed has become paramount to such a high degree that there is no machine on the market today capable of satisfying the full demand of modern computational methods. The most advanced machines have greatly reduced the time required for arriving at solutions to problems which might have required months or days by older procedures. This advance, however, is not adequate for many problems encountered in modern scientific work and the present invention is intended to reduce to seconds such lengthy computations.'

From the Electronic Numerical Integrator and Computer (ENIAC) patent (No. 3,120,606), filed 26 June 1947. Cited in (Weik, 1961). ENIAC was the first general-purpose electronic programmable computer.

Barely out of its first decade, digital computer technology was characterised as disruptive (enabling or causing radical change): as early as 1961, ENIAC, the first electronic programmable computer, unveiled in 1946, could be described as an achievement 'which literally ushered in an entirely new era in this century of startling scientific accomplishments' (Weik, 1961) (Box 1). During the second half of the 20th century a number of factors together accelerated the establishment and growth of computational modelling and simulation, and the digital computers they rely upon – a grab bag of new and extant intellectual and material innovations across a range of disciplines and industries, advances in hardware, and the development of particular conceptual tools, like software. These intellectual and technological influences include a long tradition of modelling as a heuristic tool for understanding large or complex phenomena; developments in mathematics; the often independent histories of analogue computing, calculating devices and instruments for information storage, processing, and analysis; external developments in electronic engineering, and military technology against a backdrop of mid-century geopolitical expediency (Campbell-Kelly et al., 1997) (Mahoney, 1988).

Modelling and simulation: the computer revolution

Box 2. From experimental science to simulation

'Originally, there was just experimental science, and then there was theoretical science, with Kepler's Laws, Newton's Laws of Motion, Maxwell's equations, and so on. Then, for many problems, the theoretical models grew too complicated to solve analytically, and people had to start simulating.'

Jim Gray, Microsoft, 11 January 2007 (Gray, 2009)

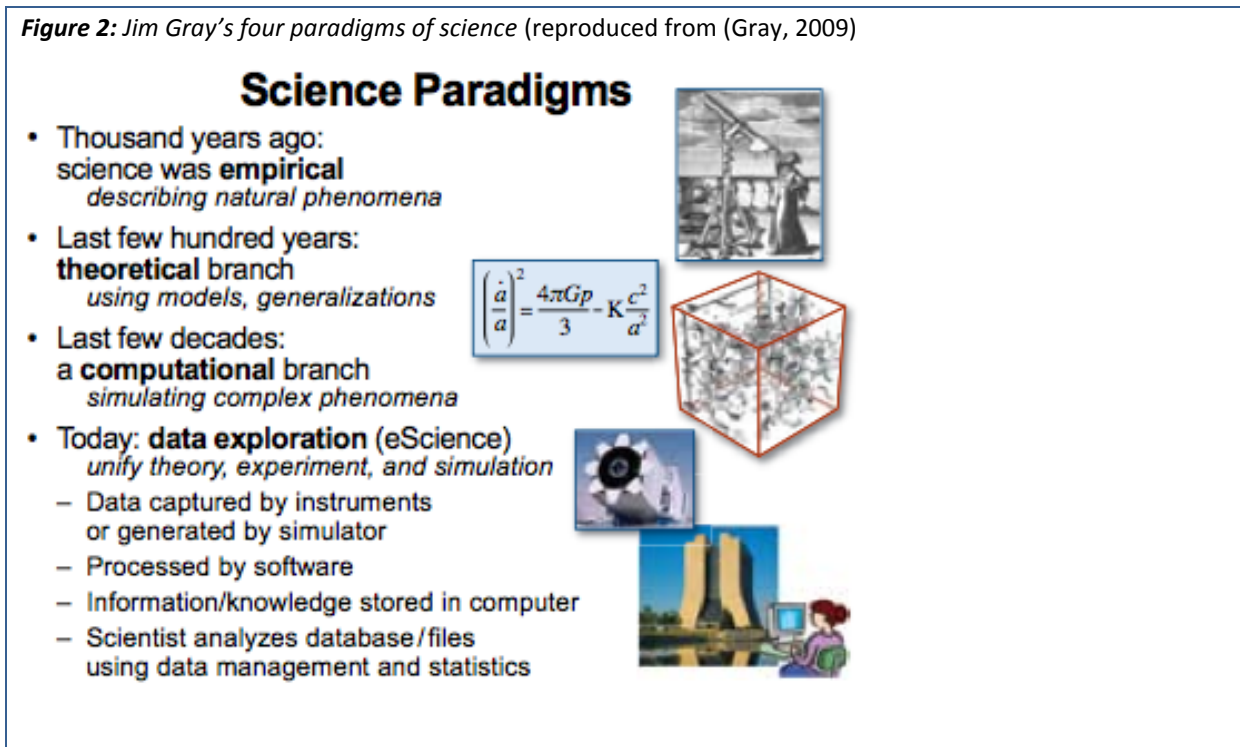
Modelling as a heuristic tool

Recent commentators have labelled the last part of the 20th century and the beginning of the 21st an age of modelling and simulation (examples include (Gray, 2009), (Winsberg, 2010), (Hey, 2010), (Strawn, 2012), (Shanmugavel, 2012) (Figure 2). But at least since the 16th century, natural philosophers and mathematicians have used the word 'model' to refer to a simplified or idealised description or representation of a system, structure, or process, proposed to improve knowledge about that system, structure, or process.² Models and simulations are essential to understanding

² 'model, n. and adj.'. *OED Online* (2013). Oxford University Press. 15 December 2013 <http://www.oed.com/view/Entry/120577>; 'model, v.'. *OED Online* (2013). Oxford University Press. 15 December 2013 <http://www.oed.com/view/Entry/120578>.

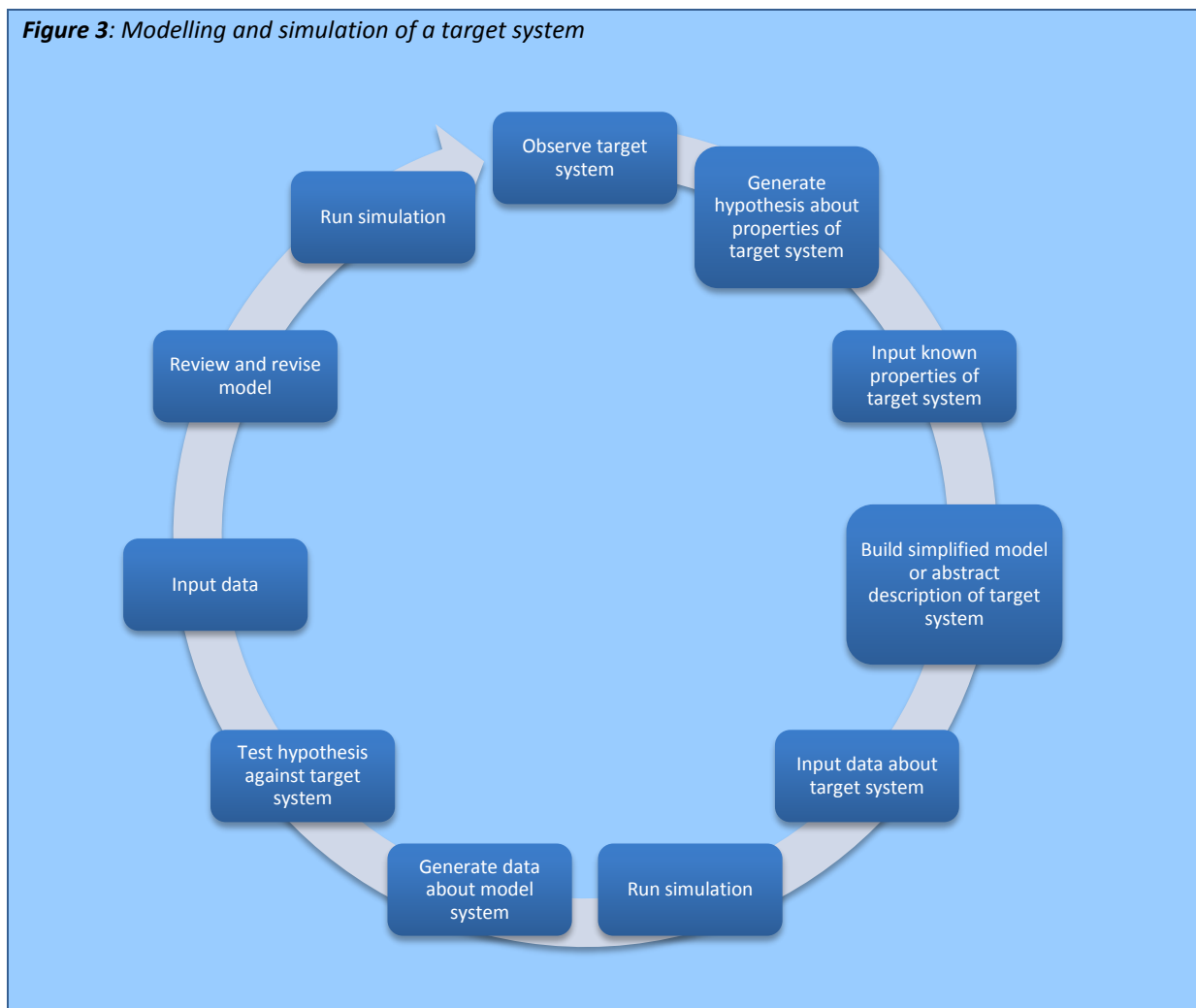
large and complex phenomena that cannot easily be studied in their entirety (Figure 3). Microsoft’s Jim Gray, in one of his last public appearances before his death in 2007, famously generalised the history of knowledge generation since the ancient Greeks to a sequence of three consecutive ‘paradigms’ culminating in eResearch (Figure 2, Box 2): experimental science, theoretical science, and his ‘third paradigm’, simulated science (which leads to Gray’s fourth paradigm – data-intensive science). However, this idea of a simplification or analogy (a model or simulation) as a basis for experimentation to reveal information about a larger system or structure existed in classical antiquity. Indeed, arguably, human beings only ever understand complex phenomena by, in some sense, modelling them (for example, Table 1).

Figure 2: Jim Gray’s four paradigms of science (reproduced from (Gray, 2009))



The equations of a mathematical model describe and relate the various relevant properties of a target system to each other. If these equations are very complex, an unaugmented human brain will not be able to ‘run’ the model. Then, a sufficiently powerful calculator – a computer – becomes invaluable. The first electronic programmable computers were built to improve researchers’ capacity to undertake the complex calculations needed for detailed modelling and simulation. Since then, the history of computers, the history of modelling and simulation, and developments in many scientific disciplines have been entangled. Over the last six decades, the development of computer simulations to study phenomena of great size and complexity has transformed modelling to revolutionise scientific discovery and research: *in silico* (‘on computer’) experiments are now virtually ubiquitous across a range of disciplines, and many industries (Hey, 2010, Winsberg, 2010).

Figure 3: Modelling and simulation of a target system



To produce a model, one abstracts a description of a system from reality (Figures 3, 4). Models cross many seemingly distinct categories and media – people use a diversity of physical models, drawings, diagrams, experimental models, hypotheses, mathematical and data-based models and simulations (Table 1). A model may help to explain a system and to study the effects of different components, and to make predictions about behaviour. For example, mechanical models called orreries were built to depict and predict the motions of the Earth and moon around the sun. Models can be mathematical rather than physical, like the Lotka-Volterra equation, which represents predator–prey population dynamics. Whether corporeal or not, models have a critically important heuristic purpose (Sokolowski et al., 2010). Researchers devote considerable resources to constructing, testing, reviewing and revising models, which are among the most fundamental tools of modern science. Models are also a critical driver of productivity improvements in technology and manufacturing, which increasingly rely on modelling and simulation rather than costly experimentation (Frigg et al., 2012), among the many direct macroeconomic effects of digital programmable computers.

Table 1. Some types of model and their uses

type of model	example	use / description
diagram	flow chart	abstract or simplified pictorial representation of information

type of model	example	use / description
infographic	subway map	a pictorial format that presents complex information quickly and clearly
technical drawing	engineering drawing	communicates required information from designers to builders
computer-aided design (CAD)	computer generated imagery (CGI)	CAD software assists in the creation, modification, or optimisation of a design.
map	digital terrain model	traffic modelling, mining and geology, drainage modelling, creation of relief maps, GIS, precision farming
spreadsheet	Microsoft Excel	organises and allows analysis of data in tabular form for business, accounting, research
opinion poll	questionnaire	models popular opinion, habits, behaviour or preferences
mathematical	fluid dynamics	flood modelling, atmospheric modelling
economic model	applied general equilibrium model	uses economic data to show how an economy might respond to technological, policy, or other external changes
computer game	Angry Birds	simple projectile modelling with computer graphics for leisure, training
physical model	planetarium	shows the relative size, position, and motion of the planets and moons in a heliocentric system
thought experiment	trolley problem ³	ethics, moral philosophy (models folk views of liability, e.g. hospital beds, organ donation, autonomous vehicles)

Importantly, a model is an abstraction – a partial yet informative representation of a target system. As Kaiser Fung explains, ‘Practitioners freely admit that their models are ‘wrong’ in the sense that they do not perfectly describe the world around us’ (Fung, 2010). Models may be ‘wrong’ in (at least) two ways: they may represent only a portion of the features of the target system, or they may fail to represent relevant features of the target system.

In the first case, the model has not failed, as models are necessarily only a partial representation of a system – to be useful, a model *must* be ‘wrong’ in this way. In the second case, even if the model fails to represent relevant features of the system, it may still successfully predict the system’s behaviour, in which case it will still be useful. This impression of lack of precision, accuracy, and completeness, in combination with cost, speed, and reaching the necessary balance between explanatory power and predictive performance of models and simulations, can have the unintended effect of engendering mistrust from the general public. However, the history of science is littered with canonical models that, while possibly wrong about the facts of the matter, transformed understanding of the natural world and influenced scholars along the way, from Galileo Galilei’s heliocentric universe to the Rutherford-Bohr model of the atom.

³ The trolley problem is a particular case of the doctrine of double effect, credited to Thomas Aquinas in *Summa Theologica* (1265–1274) (McIntyre, 2011). Advocates propose that consequentially identical acts may be morally different. See (Foot, 1967) for an early elaboration of the trolley problem.

Box 3. A model for all seasons

Finite element models are one trade-off between increased complexity, cost, and fidelity, ‘modelling large or complex objects by decomposing these elements into a set of small elements, then modelling the small elements’, analogous to the notion that connecting many tiny straight lines approximates a circle. The technique has been generalised for the numerical modelling of physical systems in a variety of engineering disciplines, including fluid dynamics and electromagnetism (Sokolowski et al., 2012). Similarly, discrete event simulation represents a system over time by capturing the system at discrete moments, and producing a finite set of snapshots of the behaviour of the system which can be generalised (Sokolowski et al., 2012). In contrast, system dynamics simulates continuous system behaviour. Time is the independent variable and the system evolves as time progresses (Sokolowski et al., 2012). These methods are appropriate under different circumstances, and the choices of the modeller inform the nature of the results.

Earlier tools for computing and modelling

From classical antiquity to the 20th century, human ingenuity produced devices or blueprints for calculating the movement of celestial bodies, for adding, subtracting and multiplying numbers, simplifying actuarial tables and storing and retrieving information efficiently.

The creation and use of some of these instruments and tools are lost to recorded history, as, for example, the 2nd century BC Antikythera Mechanism, which appears to be an ancient analogue device used to calculate the cycles of the solar system.⁴ Some devices, like the 1671 step reckoner of Leibniz and other non-programmable calculating devices, or Charles Babbage’s scaled-down prototype of his unbuilt Difference and Analytical Engines, which anticipated many features of modern programmable computers, appear with hindsight as technological or intellectual dead ends or curiosities. Regardless of their prescience, contemporary ingenuity, and innovation, they probably did not significantly influence later designs, although the creativity and foresight of their devices may be celebrated.⁵

Still other designs may have motivated subsequent engineers, consciously or otherwise, whose prototypes in turn may have influenced the 20th century electrical engineers and mathematicians who built the first successful programmable electronic computers. For example, the punched cards of Joseph Marie Jacquard’s 1804 loom came to revolutionise information storage and retrieval, and inspired Herman Hollerith to devise his Electronic Tabulating System, patented in 1889, and used by the US Census Office. Hollerith’s Tabulating Machine Company eventually merged with three others to become the International Business Machines Corporation – IBM. Punched cards were a mainstay of IBM’s electronic computers well into the 1970s (Rheingold, 2000).

A number of intellectual breakthroughs were equally important in the design of digital programmable computers, for example, Leibniz’s and Newton’s 17th century contributions to calculus, Leibniz’s description of binary in 1703, and the mid-19th century insight that led George Boole to develop Boolean algebra, which has been called ‘the mathematical linchpin that coupled the logical abstractions of software with the physical operations of electronic machines’ (Rheingold, 2000) (Boole, 1854).

Twentieth-century geopolitics and the programmable electronic computer

In the mid-20th century, a desperate arms race focused the minds of scientists and bureaucrats, and the treasuries of nations. At the University of Pennsylvania’s Moore School of Electrical Engineering, scientists of the Manhattan Project brought together mathematical innovation, improved technical precision, and technological ingenuity, to design and build the Electronic Numerical Integrator and

⁴ The Antikythera Mechanism, dated to around the 2nd century BC, is more complex than any such device known from the next thousand years (see the Antikythera Mechanism Research Project, <http://www.antikythera-mechanism.gr>).

⁵ Leibniz and Babbage references – also the Pascaline might be a good example

Computer (ENIAC), the first general-purpose electronic programmable computer. Unveiled in mid-1944, ENIAC, a 27-tonne Leviathan, was constructed to compute ballistic firing tables for the United States Army's Ballistic Research Laboratory. It was first used to model the feasibility of a hydrogen bomb; its success in this endeavour persuaded the US government of the practicability of electronic computation for military research. Before its retirement in 1955, ENIAC's processing power was brought to bear on a number of other fields, including meteorology, atomic energy, cosmic ray studies, thermal ignition, random-number studies and wind tunnel design. It was available to universities at no charge (Moye, 1996) (Ceruzzi, 1986a) (Winsberg, 2010).

Knowledge circulation between institutions and laboratories in Britain and the US was a critically important factor in early developments in programmable computing (Yost, 2013). During the 1930s and 1940s, the ideas of several polymaths, including the Cambridge and Princeton-educated British cryptographer, mathematician and philosopher Alan Turing and the Hungarian-American mathematician and physicist John von Neumann, were particularly influential in both countries. Without this vibrant technological and intellectual exchange, marked by both competition and cooperation, the development and commercialisation of digital programmable computers in the Anglo-American context may have taken a very different and possibly slower trajectory, as the parallel contemporary history of computing in the Soviet Union suggests. While there may have been geopolitical factors other than isolation at play in the divergent history of Soviet bloc computing, Australia offers another parallel history of computer design in relative isolation from the US and Britain in the 1940s and 1950s (Box 4).

Box 4. CSIRAC: Australia's first digital computer

The Council for Scientific and Industrial Research (CSIR, later CSIRO) designed and built Australia's first electronic programmable computer, CSIR Mark 1 (later called CSIRAC, the 'CSIR Automatic Computer'), in the late 1940s. CSIRAC was designed, if not in isolation from, then largely independent of, contemporary efforts in the US and Britain, by ICT pioneer Dr Trevor Pearcey and his colleagues radiophysicist Maston Beard and CSIRAC's first programmer, Geoff Hill. CSIRAC, housed at the CSIR Radiophysics Laboratory in Sydney, ran its first program late in November 1949.

On its completion, CSIRAC was the fourth digital computer in the world with a capacity to store programs (unlike ENIAC, which had to be reprogrammed manually in a time-consuming process for each new set of calculations). Covering more than ten square metres of floor space and weighing seven tonnes, using enough electricity to power a suburban street, CSIRAC, diminutive by ENIAC's standards but still a monster, had only a fraction of the processing power of a modern smart phone, running at 0.001 megahertz, with 2000 bytes of memory and 2500 bytes of storage. But when fully operational it was a thousand times faster than any machine available elsewhere in Australia at the time.

From 1951 to 1955, the computer provided a service to all of CSIRO, when it was used for more than 300 projects, performing large and complex calculations rapidly, which allowed modelling and simulation in research as diverse as meteorology, the thermal properties of buildings, and banking. It also helped transform Australia's infrastructure, environment, and cultural landscapes, playing a critical role analysing river flow during the Snowy Mountains hydroelectric scheme, which is still the largest engineering project undertaken in Australia.

Anticipating modern multimedia applications, between 1951 and 1953 Hill programmed CSIRAC to play popular melodies, broadcast through a loudspeaker. It performed the world's first digital music, the Colonel Bogey March, to an international audience during Australia's first computer conference in June 1951.

In 1954, in light of the, CSIRO terminated the CSIRAC program, because of the development of solid-state devices like the transistor in the United States, which replaced cumbersome, unreliable vacuum tubes, leading to much faster, smaller computers. Dr Pearcey regretted this decision to his death in 1998, regarding the

organisation as having failed to capitalise on Australia's early leadership and innovation (Pearcey, 1988). But Melbourne computer historian Peter Thorne believes the growth of a globally significant hardware industry in Australia was unlikely, given the export restrictions and cost caused by Australia's physical isolation from the largest markets.

From 1956 until 1964, CSIRAC was housed at the University of Melbourne, where it processed more than 700 projects during about 30,000 hours. These calculations ranged from commercial applications, including home-loan repayments, to models and simulations which helped in the design of skyscrapers.

CSIRAC was retired in 1964. It was then the oldest computer still in operation. Although no longer operational, it is housed in the Melbourne Museum, the last intact memorial of the first age of electronic computing.

(CSIRO, 2011) (CSIROPedia, 2011) (Johnson, 2001)

By May 1951, American and British companies began producing electronic computers commercially. By 1953, IBM had developed the Model 650. In 1959 the company released the 1401, a smaller, cheaper, more modestly powered computer for business use, and the 1620, marketed as an inexpensive 'scientific computer', which sold about 2000 units before IBM discontinued the line in 1970. Selling in the thousands, the Model 650 'became the Model T of computers'.⁶ The even better targeted 1401, rarely used for science or engineering, sold in the tens of thousands, cemented IBM's market dominance, and established computer modelling as a tool for business as well as science (Ceruzzi, 1986b, Ceruzzi, 2005).

Pioneered as a scientific tool by mathematicians, nuclear physicists, and meteorologists in the period following the Second World War, computer simulation has rapidly become indispensable in a variety of fields of research. Following its use in the Manhattan Project in 1945 to model nuclear detonation on ENIAC, the growth of computer simulation matched, motivated, and was driven by the rapid evolution of computers in the second half of the 20th century (Winsberg, 2010).

Computer models and simulations have profoundly changed what it means to understand a system (Box 7). Computer models and simulations build on, and are a replacement for, mathematical models and for physical experiments. Computers can be regarded as 'just' a tool to enhance scientific modelling, but their ubiquity, power, efficiency, and fundamentally important role in the 21st century global data ecosystem could be said to have generated a qualitative change in scientific modelling and experimentation, driving scientific and technological change, and through these, economic and social change in the late 20th and early 21st centuries, making them the 'general purpose' technology *par excellence* (Jim Gray's 'third paradigm' – (Strawn, 2012); (Winsberg, 2010) (Figures 1, 2, 4).

The rate of change: the rise and rise of digital computing and computational modelling

Moore's Law and friends

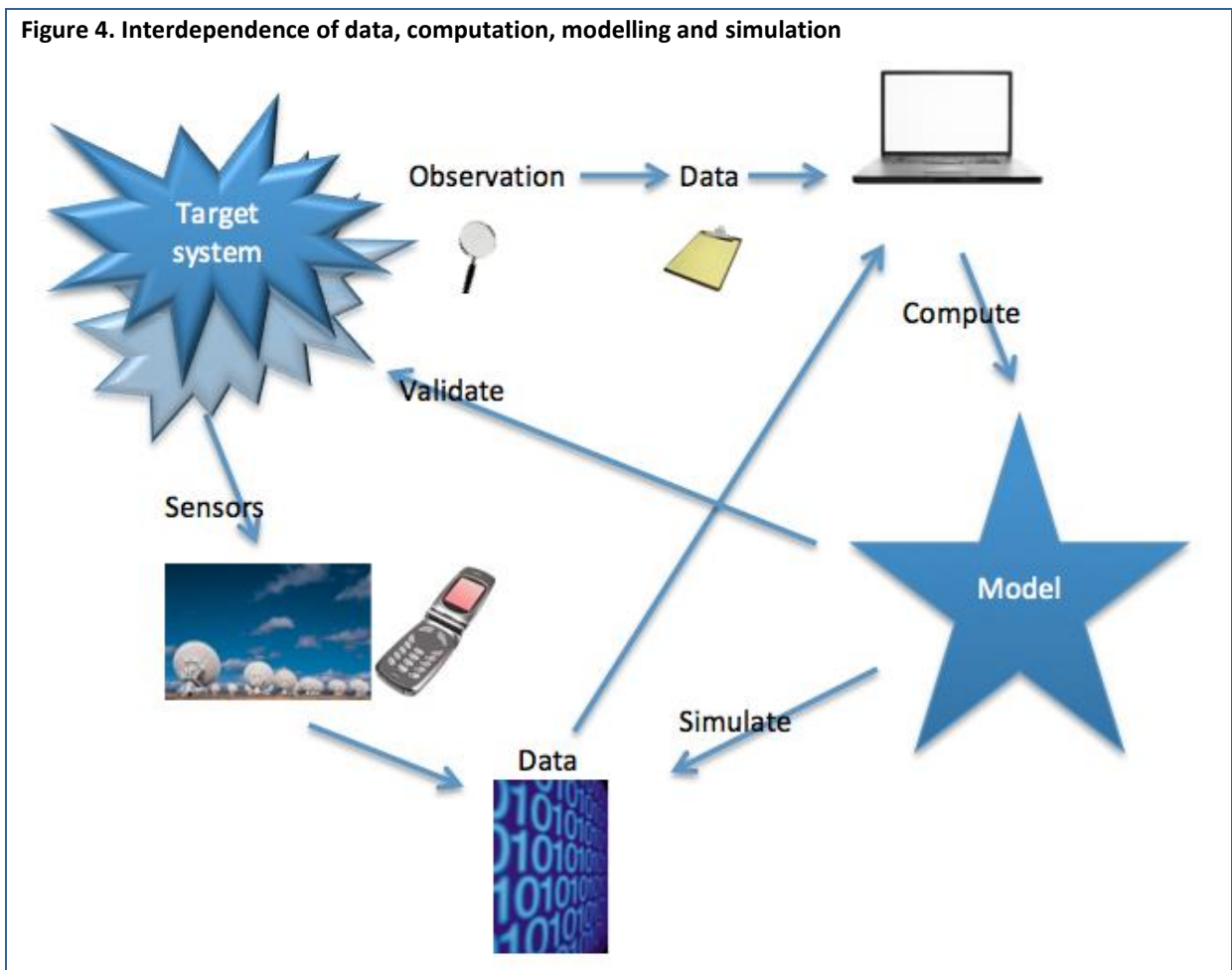
In a 1965 paper, in what he has since described as a piece of 'lucky extrapolation', Gordon E. Moore, co-founder of Intel, observed that the number of transistors on integrated circuits had doubled approximately every two years (Moore, 1965) (Intel, 2005). In predicting that this increase would be accompanied by falling consumer cost and improved computing speed, power, memory capacity and efficiency, 'Moore's Law', as Moore's observation is known, describes not so much a law of nature as a powerful driver of social, economic, and technological change over the last six decades. Similar

⁶ The rise of the Ford Motor Company's iconic Model T, and its influence in automotive history, is discussed in WP 012 *Locked into the car*.

'laws' predict the roughly exponential rate of change for associated ICT capabilities including network capacity, storage, data and bandwidth availability, and network connection, which has increased the influence of ICT on most aspects of the global economy (Rauch, 2001).

Chip manufacturers, futurists, economists, physicists, and engineers debate whether there is an outer limit to Moore's Law. Furthermore, to the extent that it has been a self-fulfilling prophecy, some commentators regard Moore's Law as being a check to innovation in solid-state technology as much as it has been an incentive for progress in a particular direction. For example, at a presentation in California in August 2013, Robert Colwell, director of the Microsystems Technology Office at the US Defense Advanced Research Projects Agency, (DARPA) exhorted engineers to consider changing 'fundamental microprocessor architecture to ensure chips are faster and cheaper to produce', instead of continuing to focus on reducing chip size and ramping up processor speeds, citing hard physical limits, but also economic parameters to the persistence of Moore's Law. Colwell emphasised the economic scaling effects identified by Moore, pointing out that 'if you're going to integrate a lot of components on a chip, there's an optimal place on that curve where you should do that. You can go beyond the optimal point, but it will cost you in terms of price per component'. In other words, while there is an upper physical limit to Moore's Law, economic factors will intervene before manufacturers reach this physical barrier. 'The day chip makers can't get return on the billions invested in making chips smaller is the day Moore's Law will break. Instead of waiting for chip economics to crash, innovation should start now'. Quantum computing, nanotechnology, biocomputing, improvements in parallel processing, distributed computing, and moving from planar to 3D chips are all areas being investigated (Shah, 2013) (Courtland, 2013) (Box 5).

Figure 4. Interdependence of data, computation, modelling and simulation



The increasing availability of computers, associated cost reduction, and growing power roughly following and anticipated by Moore's Law undoubtedly played an important role in the first decades

of computer modelling. As a consequence of the effect observed and predicted by Moore, with improved processing speed and power and decreased cost, researchers could model and simulate increasingly large and complicated scenarios. The greater complexity of models produced higher fidelity simulations, and with them, more data. This fundamental feature of modelling and simulation is a critical part of the feedback loop that drives data's economically, scientifically, democratically, and socially disruptive potential (Figure 4) (see WP16 *Technologies for data*).

While the initial acceleration in computing power was clearly critical to the successful commercialisation and widespread adoption of computers as tools for scientific modelling, other influences were also crucial in the early days of electronic computing. As the use of computers and commercial software have become increasingly pervasive, these other influences have grown in importance. As Michael Mahoney observed, initially, 'largely exogenous factors in the electronics industry' expanded the possibility for computer memory and speed, lowering the cost of hardware and improving the resilience of the machines. These improvements enabled programmers to 'take practical advantage of research into programming language'. Previously blue-sky research 'of multiuser systems, interactive programming, or virtual memory' then capitalised on developments in hardware 'at the same time that they drew out the full power of a new generation of machines'. For instance, over recent decades, computer gaming has been the main driver of increased performance and reduced cost. Researchers now use top-end gaming graphics cards for modelling and simulation. Advances in the components of graphics cards, including graphics processing units, and improvements in modelling and simulation, have been mutually reinforcing. These organising and coordinating effects are self-perpetuating. 'Just as new architectures have challenged established forms of programming, so too theoretical advances in computation and artificial intelligence have suggested new ways of organizing processors' (for instance, via parallel processing), demonstrating the critical role of fundamental research funded by the state at all stages of the commercialisation pathway for digital computing technologies (Mahoney, 1988).

A critical early breakthrough, distinguishing ENIAC's late contemporaries and their successors from ENIAC itself, was the innovation allowing computers to store programs, rather than forcing programmers to undertake the time-consuming process by hand every time a researcher needed to run a new program. This improved the machines' capacity to function efficiently as general purpose calculators. Heat transfer and energy efficiency were key limits to the earliest electronic computers, which were room-sized monsters with an enormous appetite for power. During the 20th century and into the 21st, organising and coordinating effects have encouraged exponential improvement in computers as well as reinforcing the unpredictable effects of serendipity (for example Figure 4). The development of the transistor freed computer engineers, manufacturers and users from the tyranny of vacuum tube circuitry – this technology was notoriously fragile and energy inefficient, severely limiting the speed and memory available on a computer, and involving a lot of time lost to maintenance (Ceruzzi, 1986b, Ceruzzi, 2005).

Box 5. The speed of change

In the 16th and 17th centuries, human computers produced logarithmic and trigonometric tables, enabling otherwise time-consuming arithmetical functions to be performed simply. By the late 18th century, specialised tables were produced which revolutionised a number of industries, improving the speed and accuracy of calculations. From the Victorian period to the 1960s, ‘computer’ described a person employed to record observations and make calculations (Campbell-Kelly et al., 1997).

In 1946, over an eight-hour day, a skilled computer could perform 400 operations, or one operation every 72 seconds. In comparison, ENIAC could multiply two 10-digit numbers accurately in 0.003 seconds, and it operated 20 hours a day, seven days a week. Performing approximately 30,000,000 elementary operations a day, ENIAC did the work of 75,000 skilled human computers (Ceruzzi, 1986b).

Thirty years later, in 1976, the Cray I supercomputer was the fastest machine of the day; with speeds of 166,000,000 Floating-point Operations Per Second (flops), it was nearly 400,000 times faster than ENIAC.⁷

By 1996, a desktop PC had 1000 times ENIAC’s processing speed and several million times its data storage capacity (Lohr, 1996). At nearly 30 tonnes, ENIAC was around 1500 times heavier than this approximately 20 kg personal computer 50 years later.

Fifteen years after this, in 2011, the 140 gram iPhone 4 could perform approximately two billion instructions per second, making it nearly five million times faster than ENIAC, 5000 times faster than a PC in 1996, and around 12 times faster than the Cray I.

Assuming that Moore’s Law, which estimates an approximate doubling of processing power every 18–24 months, is as reliable a predictor of advances in processing in the next few years as it has been for the last 40, the global processing power of mobile CPUs could grow 40 to 60-fold in the five years between 2011 and 2016 (Bauer et al., 2012).

‘The technologies enabling supercomputers are also evolving. In the past, engineers focused on processor improvements. However, as they approached the enhancement limits at clock level, referred to as the ‘power wall’, they increasingly concentrated on architectural enhancements. Vector architectures are gradually being replaced with massive parallel architectures. As a result of technical progress over the years, the performance of supercomputers has been growing at a faster rate than semiconductor density. In the last 11 years alone, it has increased 1000 fold. At the current pace of development, the world’s fastest supercomputer will hit 1 exaflops (one quintillion flops) by around

2018.’ (Fujitsu Australia, 2012)

Such exponential change defies effective visual representation and breaks down the power of analogy: In the same way that describing the speed of an Airbus A350 passenger jet in terms of horsepower has very limited heuristic worth, comparing the speed, power, and memory of an iPhone in 2011 to the processing power of a human computer working an eight hour day in 1946 is largely meaningless, at around 400 billion ‘person power’, or roughly four times the number of people who have ever lived (Haub, 2002, Haub, 2011).

Some researchers have an insatiable appetite for processing power and memory – scientists who work in geodynamics, astrophysics or climate modelling, to name but three disciplines. For these fields, the power requirements of the upper limits predicted by Moore’s Law on the evolution of high-performance computing remain very relevant (the power demanded by a processor is proportional to the cube of its frequency, so doubling a processor’s frequency requires an eightfold increase in power) (Service, 2012). However, for many other fields of research and development, a

⁷ Computer History Museum Exhibit ‘Timeline of computer history’, <http://www.computerhistory.org/timeline/?category=cmpttr>.

desktop computer provides sufficient processing power to run detailed models and quite complex simulations. Programming innovations and the availability of off-the-shelf software have significantly reduced the cost, processing power and memory required for a great many applications. Such factors, together with the revolution in personal computing during the 1980s and 1990s, have transformed these disciplines and industries.

Box 6. Programming – the essential innovation

'The invention of computer programs that translated commands simple for humans to learn into commands the computer needs to know, broke through the last barrier to the spread of the new invention. Of course the widespread use of computers today owes a lot to the technical revolution that has made the circuits so much smaller and cheaper. But today's computers-on-a-chip, like the 'giant brains' before them, would never have found a large market had a way not been found to program them. When the low-cost, mass-produced integrated circuits are combined with programming languages and applications packages (such as those for word processing) that are fairly easy for the novice to grasp, all limits to the spread of computing seem to drop away.'

(Ceruzzi, 1986b)

Democratising computing: questions in the history of technology

The industrialisation and domestication of programmable electronic computers and the accompanying tools to democratise computer modelling and simulation reflect each of five major themes identified at the beginning of this case study – the relationship between science, engineering, and technology; the extent to which technological innovation creates or responds to demand; patterns of technology transfer within and between cultures, including adaptation and adoption of technologies within a society; the roles of government and industry in fostering and directing technological innovation and development; and the role of economics in innovation.

Science, engineering, and technology

The steady rise in the speed and power of computers, increasingly compact and cheaper memory, economic scaling leading to lower production costs, the availability of commercial software, mobile platforms, and innovations in programming have all contributed to the near ubiquity of computers as tools for modelling, and of modelling and simulation as tools for just about every modern field of enquiry and industry, from the social sciences to meteorology, manufacturing and the resource sector. In turn, improvements in computer modelling and simulation have had flow-on effects which have improved computer and electrical engineering. This mutual reinforcement and interdependence exemplifies the often intimate, recursive relationship between engineering, technological innovation, and scientific research. For example, as Mahoney observed of the early history of electronic computing, transformative ideas like software required advances in hardware for their implementation at the same time that the realisation of these ideas 'drew out the full power of a new generation of machines' (Mahoney, 1988) (see also (Ceruzzi, 1986a), and Box 6). The advances in modelling and simulation that have followed increases in computing capacity and the evolution and democratisation of programming have in turn provided sophisticated tools for technicians to engineer better computers (it is these positive feedback loops and the promise of machine learning and artificial intelligence (AI) that excite singularity enthusiasts like futurist Ray Kurzweil and mathematician Vernor Vinge).

Advances in computer modelling and simulation have also effected a qualitative change in what it means to understand a system. Large and complex datasets and sophisticated modelling software, both bespoke and off the shelf, enable researchers across all disciplines to capitalise on the heuristic potential of modelling and simulation to transform understanding of their disciplines (Boxes 7, 8).

Simulations generate data, fuel for data analytics, which in turn feeds into computational models, improving the understanding of a system (Figures 1, 4).

Box 7. A model for the building blocks of life: computer simulation enhances conventional modelling

In the mid-20th century, biologists were concerned with the physical structure of the DNA molecule, and the connection of structure to function. Biologist James Watson and physicist Francis Crick published the first double-helix model of DNA structure in *Nature* in 1953, derived from Rosalind Franklin's and Maurice Wilkins' x-ray diffraction image of 1952 (Watson et al., 1953) (Watson & Crick 1953, 737-738). Modelling in wire, Watson and Crick worked out the structure of DNA to explain the molecule's characteristics and known functions: 'This [(DNA)] structure has two helical chains each coiled round the same axis ... Both chains follow right handed helices but ... the sequences of the atoms in the two chains run in opposite directions. ... The bases are on the inside of the helix and the phosphates on the outside' (Watson et al., 1953) (Peters n.d.).

Sixty years later, computational biologists in the United States created the first software simulation of an entire organism, *Mycoplasma genitalium*, a single cell bacterium that lives in human genital and respiratory tracts, using DNA and RNA sequences and post-genomic data (Karr et al., 2012) (Markoff, 2012). Researchers used data from more than 900 scientific papers and observed that the model, of the simplest free-living organism, was pushing computational limits: 'Right now, running a simulation for a single cell to divide only one time takes around 10 hours and generates half a gigabyte of data ... I don't know that anyone has ever asked how much data a living thing truly holds' (Markoff, 2012).

Box 8. Modelling a continent: from field work and fibreglass to digital terrain mapping

Earth sciences disciplines have undergone a technical and conceptual shift since the 1940s when University of Melbourne geologist E.S. Hills painstakingly assembled a physiographic model of Australia. Modern digital terrain maps signal a qualitative change in what it means to model a continent, and, in some sense, to be a geologist.

Democratising knowledge and production

Hills' model initially involved military funding and took over a decade to complete. It is a fixed-scale model with exaggerated vertical scale. There is no way to improve detail. In contrast, digital terrain mapping is flexible. It can be bought off-the-shelf. Small mining companies, independent researchers or graduate students can purchase software packages. Digital terrain mapping is now part of a canvas onto which problems about the world can be painted.

What is lost?

A degree of transparency about what people do not know (but it is dangerous to assume that Hills' original physical model was transparent)

The chain of production has changed, and the craft involved in producing a 3D physiographic model from scratch has become obsolete.

Researchers can now use satellite images and aerial photography to make observations and collect data on computers, which is a major change in the nature of survey and field work.

Recent initiatives include National Map⁸, launched by NICTA in July 2014, which provides web-based access to geospatial datasets from Australian Government agencies including Geoscience Australia, the Bureau of Meteorology and the Australian Bureau of Statistics, and which will facilitate the opening of data from other Federal, state and local government agencies; and AuScope, a national geoscience and geospatial infrastructure system launched in 2007, funded by the Australian Government to meet the science, data and infrastructure needs of Australian geoscientists in government, industry and research, to improve understanding of the structure and evolution of the Australian continent.

Advances in digital computing, and associated opportunities in modelling and simulation since Hills built his celebrated model, have improved the capacity of geologists to 'see' underground. For example, petroleum exploration has been revolutionised by massive improvements in the commercial production of legible 3D seismic images over the last 40 years, allowing geologists to look inside the Earth with much greater clarity than 2D profiles could ever have produced (Rauch, 2001).

Technology and demand

The first modern computer scientists did not know that they were creating a tool that would transform science, research, industry, commerce, wellbeing and leisure in the 20th century, and would set the stage for a revolution in information and communications technology in the 21st. But the ready adoption of smaller, mass-produced models like IBM's Model 650 for commercial and industrial purposes suggests strongly that during the 1950s and 1960s, business recognised a need that could be filled by the new technology (Ceruzzi, 1986a). In this sense, the commercialisation and industrialisation of early programmable electronic computers both created and filled the subsequent market need for desktop and personal computers in the 1980s.

The mechanisation of routine intellectual tasks seems, with hindsight, to have been a logical next step for industrialisation, and one that encoded its own future innovations. For example, substituting programmable electronic computers for human computers allowed faster and more complex mathematical modelling, which in turn allowed breakthroughs in computer design and manufacture (see Box 5). And the productivity improvements and reduction in staff costs over time appealed to industry and small business, speeding adoption and focusing R&D funds (Ceruzzi, 2003). The rapid uptake of computers for business and industry provided designers and manufacturers with incentive to improve the facility of computers and software for such purposes. This commercialisation contributed to their decreasing cost, a key barrier to their adoption, and eventual pervasiveness in laboratories, offices and households (Box 6).

Historian of technology Paul Ceruzzi described the 1960s transformation of the computing industry and another reinvention of computers, with few equals to the industry's 'rate of technological advance ... and the rapid obsolescence of existing products'. IBM, with nearly three-quarters of the market from the late 1950s, recognised this as a problem and opportunity. The company created a large research department with laboratories on both coasts of the United States and in Europe, to capitalise on advances 'in solid-state electronics, tape and disk storage, programming languages, and logic circuits' (Ceruzzi, 1998). Supporting such pioneering research, much of it expensive and with a considerably longer incubation period than directly applied research, allowed IBM to exploit its existing competitive advantage while insulating its customers as much as it could from 'the shock of adoption', including by retaining the punched card as a fundamental input mechanism.

Scarcely modified since the 1930s, punched cards 'served IBM's computers through the 1960s and beyond', ensuring the company's continued market dominance, but providing a brake to certain kinds of innovation.⁹ With no clear demand for speedier innovation from the business sector, had government support for computer research, particularly from the US Department of Defense, not

⁸ National Map <http://nationalmap.nicta.com.au/>.

⁹ IBM still dominates the biannual Top500 Supercomputer List. On the June 2013 list, five of the top ten fastest supercomputers were built by IBM, and 34 of the top 100 (Knapp, 2013).

increased considerably from the 1950s, ‘the computer industry might have gone on this way for decades, just as the US auto industry dominated by three firms, achieved an equilibrium into the 1980s’ (Ceruzzi, 1998),pp110-112. As Ceruzzi observed, the military’s demands for computation and simulation, along with the demands of other branches of the federal government, provided the generous budgets and a degree of intellectual autonomy which impelled the evolution of large mainframe installations, dominated by the IBM 7000 series. Reciprocally, ‘research in solid-state physics and electronics produced a fundamentally different type of computer’, and ‘a key group of individuals leveraged that research to redefine the industry’.

IBM saw the business potential of a cheaper, smaller computer, and realised that modelling and simulation are tools for business as well as scientists. It is notable that the rise of operations research (a subfield of mathematics which applies advanced analytical methods and modelling to decision-making and is now regarded as a critical business tool) paralleled the rise of electronic computers. One of the founders of operations research, John von Neumann, is also a luminary of early electronic computer engineering.¹⁰

In this way, a bespoke device for military and meteorological modelling became an indispensable business tool when mass-produced. The accompanying cost reductions reinforced its accessibility for researchers as well as industry. Then a huge injection of government funding provided the impetus for researchers outside large industrial laboratories – in particular in research laboratories at prestigious universities – to deliver powerful new tools (and increase the demand) for calculation-heavy academic research, and reveal whole new fields for study (Ceruzzi, 1998),pp112-113. With computers increasingly available and increasingly important, the growing influence of the field of operations research (which demanded sophisticated modelling from businesses), the development of off-the-shelf simulation tools, and the rise of increasingly affordable personal computing from the mid-1970s, the stage was set for a revolution.

Technology transfer, adoption and adaptation

From the room-sized, cumbersome military tools of the 1940s, to word-processing and spreadsheet software in the 1980s, to the tablets and smart phones of the second decade of the 21st century, the development of electronic programmable computers sheds light on patterns of transfer between cultures of science, technology, business, and domestic spheres during the late 20th century. Through a series of economic, intellectual, and technological tipping points and convergences, improvements in the cost and effectiveness of various constituent parts of computers increased the payoff for improving other components. ENIAC and its successors augmented the capacity of researchers in calculation-intensive sciences in the 1940s, before IBM’s mass-produced Model 650 and its successors began to transform business practice in the 1950s. By the 1970s, mass marketing of personal desktop computers was underway and Apple had begun to market its user-friendly windows-like interface and the computer mouse, launching ‘the computer for the rest of us’, the Macintosh personal computer, on 24 January 1984 (Cassidy, 2014) (Gallo, 2014). From 1986, networked computing and the internet began to transform computers, computing, and patterns of use again. Meanwhile, supercomputers and eventual improvements in parallel processing rapidly transformed calculation and modelling-intensive fields of research and industry such as astrophysics, meteorology and climate research, geophysics, molecular biology, theoretical physics, engineering and economic geology.

Decreasing costs reduced barriers to adoption, and this further reduced costs. Electronic computers began to invade the domestic and leisure spheres, following their adaptation from specialist calculating machines, adoption by government agencies, business and industry, and the

¹⁰ It is an interesting coincidence that, in researching the construction of his Difference Engine, another celebrated early ‘computer scientist’, Charles Babbage, wrote what is regarded as the first published text on operations research, his 1832 *On the economy of machinery and manufacture*.

development of demotic tools for computer programming, modelling and simulation. Yesterday's high-performance computer is today's smart phone (see Box 5). This technology enables the work of students and citizen scientists, it facilitates business modelling, the provision of social services by governments at all levels, local councils to monitor traffic, energy firms and householders to monitor domestic energy use, and has improved the functioning of emergency services. Leisure, too, has changed. Computer generated imagery has revolutionised the film and television industries as well as providing crucial capability to military, civil and commercial users. The global positioning system has transformed domestic and leisure travel, and even smart phone apps such as the slingshot game 'Angry Birds' and immersive runners' tool 'Zombies, Run!' are simple simulations (Table 1).¹¹

With the unveiling of Apple's Macintosh in early 1984, the stage was set for personal computers as aspiration objects for lay people: 'The Macintosh changed everything. It was a computer with a price tag that was within reach for many, and more importantly, it was a computer that almost anyone could operate without going to school to become an expert' (Cassidy, 2014). Beyond introducing a new kind of personal computer, Steve Jobs' Macintosh launch, and his focus on design and usability, is credited with generating a paradigm shift in the presentation of computing, and the staging of product launches (Gallo, 2014) (Gallo, 2014). Not just a tool for hobbyists, gamers, and hardware enthusiasts, and a status symbol for the wealthy, from 1984 personal computers began their transformation into near-ubiquitous pieces of domestic and workplace material culture. The advent of genuinely portable personal computers in the shape first of laptops, then notebooks, smart phones and tablets, in conjunction with wireless and mobile internet access, changed the nature of computing again. Their bundling with other 'extended mind' technologies and techniques like the telephone, calendar, diary, list, address book, calculator, and camera, and the ready availability of search engines, electronic news media, and social networking sites, has changed personal computers into repositories of memory, devices for the negotiation of human relationships, essential business tools, and platforms for skill transfer, creativity, and learning.

The first electronic programmable computers were envisaged as bespoke research tools for counting more quickly and accurately (a view which contrasts interestingly with Ada Lovelace's vision in the 1840s that the successors of Charles Babbage's analytical engine would be able to 'compose elaborate and scientific pieces of music of any degree of complexity or extent' – see Box 9); the creators of ENIAC (J. Presper Eckert, Jr. and John W. Mauchly) and its contemporaries and immediate successors did not initially conceive that there would ever be need for more than a handful of computers in the United States (Ceruzzi, 1986a). The fastest calculating machine of its day in the United States, ENIAC operated at a speed of a few hundred flops (Floating-point Operations Per Second). As of June 2013, the fastest computer in the world, China's Tianhe-2, is capable of more than 30 petaflops (a petaflops is one quadrillion, or a thousand trillion, flops) (Knapp, 2013), 60 trillion times faster than ENIAC, and many orders of magnitude more energy efficient (see Box 5). Fujitsu Australia recently predicted the emergence of a business market for supercomputers 'beyond the R&D labs' as, for example, detailed simulations can significantly reduce the cost for aircraft manufacture by removing the need to build a prototype, and the massive processing power of supercomputers can facilitate big data analytics for businesses. Masahiko Yamada, the President of

¹¹ For example, Mathematical Simulation Technology blog (2013). 'Angry Birds', <http://mathsimulationtechnology.wordpress.com/angry-birds-mst/>: 'Angry Birds uses basic 2D Newtonian mechanics: $dx = v dt$; $dv = F dt$; $F = (0, -1)$, with F a constant downward gravitational force and the slingshot controlled by giving initial position x and velocity v on the touch screen, and the parabolic trajectory of the launched bird being computed by time-stepping. In the update Angry Birds Space the force F is generalized to gravitational pull from point masses which allows more intricate shots. Angry Birds also includes rigid body mechanics for simulation of the effect on the structures of successful shots, augmented by sound effects as an important part of the game experience'.

Fujitsu Japan's Technical Computing Solutions Unit, claims that 'a few decades from now, supercomputers will be a crucial part of our social infrastructure'.¹²

But personal computers, tablets, and smart phones, with processing power, speed, and memory unimaginably more than even Eckert, Mauchly and their contemporaries could have conceived, already pervade professional and domestic life in the form of a 'supercomputer in your pocket' (Bauer et al., 2012). At around 100 megaflops in processing power, a million or so times faster than ENIAC, smart phones are increasingly providing affordable and portable tools for rapid and complex calculations and modelling, invaluable in developing countries, emergencies, remote fieldwork, and for non-government and not-for-profit organisations. For example, mechanical engineers at MIT have produced an app that can provide real-time and reliable simulations from a smart phone anywhere on Earth (Bartlett, 2012).

Box 9. A new, a vast, and a powerful language

'Supposing, for instance, that the fundamental relations of pitched sounds in the science of harmony and of musical composition were susceptible of such expression and adaptations, the engine might compose elaborate and scientific pieces of music of any degree of complexity or extent'.

'[With the Analytical Engine] a new, a vast, and a powerful language is developed for the future use of analysis, in which to wield its truths so that these may become of more speedy and accurate practical application for the purposes of mankind than the means hitherto in our possession have rendered possible. Thus not only the mental and the material, but the theoretical and the practical in the mathematical world, are brought into more intimate and effective connexion with each other'.

'The engine can arrange and combine its numerical quantities exactly as if they were letters or any other general symbols; and in fact it might bring out its results in algebraical notation, were provisions made accordingly ... it would be a mistake to suppose that because its results are given in the notation of a more restricted science, its processes are therefore restricted to those of that science'.

Augusta Ada King, Countess of Lovelace (Menabrea, 1842)

The roles of government and industry in technology and innovation

The history of the rise of electronic programmable computers provides insight into the roles of government and industry in fostering and directing technological innovation and development. The earliest computers had extremely large upfront research and development costs and would not have been feasible without the significant public funding encouraged by the contemporary military imperative – but, in partnership with government, industry commercialised the technology and allowed for its widespread adoption, apprehending new and pervasive uses which were not conceived by its inventors. Further breakthroughs in the United States accompanied an increase in government funding and a new collaborative model for R&D (involving academic researchers, the computer industry, the military, and other government bureaucrats) from the 1950s.

The breakthroughs enabled by computational modelling and simulation, as well as the high capital costs of the tools that support it, present a number of policy challenges related to funding, planning, and legibility.

1. To what extent should governments anticipate market failure, and pick winners by funding particular sorts of infrastructure? Can the lessons of the rise of the digital computer be generalised to other technologies?

¹² Fujitsu Australia, 'The supercomputing imperative', <http://www.fujitsu.com/au/solutions/supercomputing/supercomputing-in-focus/>

Box 10. A complex university–industry–government partnership

In 2012, updating their famous ‘tire tracks’ diagram, the US Committee on Depicting Innovation in Information Technology, the Computer Science and Telecommunications Board (CSTB), the Division on Engineering and Physical Sciences, and the National Research Council observed that fundamental research in information and communication technologies conducted in universities and industry *‘has led to the introduction of entirely new product categories that ultimately became billion-dollar industries. It reflects a complex research environment in which concurrent advances in multiple subfields — in particular within computer science and engineering but extending into other fields, too ... — have been mutually reinforcing, stimulating and enabling ... leading to vibrant, innovative industries’.*

The authors observed that *‘innovation in IT is made possible by a complex ecosystem encompassing university and industrial research enterprises, emerging start-up and more mature technology companies, those that finance innovative firms, and the regulatory environment and legal frameworks in which innovation takes place. It was within this ecosystem that the enabling technologies for each of the IT industries illustrated in Figure 1 were created. The government role has coevolved with the development of IT industries: its programs and investments have focused on capabilities not ready for commercialization and on the new needs that emerged as commercial capabilities grew, both of which are moving targets. A 2009 CSTB report, which examined the health of this ecosystem and noted the challenges posed to the U.S. position in IT leadership, underscored the critical importance of this federal investment.’*

Given the degree of serendipity and ad hocery in the rise of digital computers, the effectiveness of a mixed government/industry funding model early in the development of digital computing, organising and coordinating effects, other factors in their emergence, and the fact that as a general purpose technology, its wider impacts in the market are hard to quantify, the rise of digital computing cannot necessarily be generalised to other sorts of technology or infrastructure. It is easy with hindsight to see a logical progression from mainframes to smart phones via personal computers as inevitable but as the divergent histories of computing in the US, UK, Australia and Russia suggest, geopolitical context, geography, and serendipity played a significant role. But it is clear that the US government’s large injection of funding for fundamental research at a number of points in the pathway to modern computing was critical to the success of the technology and the strength of the US industry. Funding for this kind of basic research cannot be precisely directed because of organising and coordinating effects, path dependence, convergence, and because when effective, it can lead to the development of wholly new classes of product, process and service (Box 10).

Models and simulations are part of the construction and validation of scientific knowledge. They are often the only explanations available for phenomena which are large and complex, or for which data are scarce; given the sparseness of data or the complexity of the system, can researchers, let alone policymakers, reliably evaluate the dependability of data arising from simulations which may inform government policy?

Subject area and modelling experts need to ensure that their data can be read and used by non-specialists, who need to be able to ask the right questions of the model. A policymaker has to establish trust that she knows what she is talking about, but can only do this if she can give a simple and convincing explanation – so the modeller needs to simplify the information he conveys in a way that is both convincing and legible.

2. How can decision-makers in government and industry make appropriate decisions about technologies they do not properly understand, let alone take account of research results produced by simulation?

While the question of expertise is not a new problem for decision-makers, the results of modelling and simulation are an increasingly important ingredient of policy, in both corporate and government sectors. When designing simulations for non-expert audiences, researchers

need to consider the end-users – CEOs, policymakers, ministers, etc. – and to strike a balance between detail and legibility. This brings into focus the importance of trust. These end-users are typically not expert in either subject matter or in the modelling technique, so if the expert cannot readily or convincingly explain why she got the result she got, the solution begins to take on black box characteristics. To avoid this problem, a reduced or simplified model is preferred, in a trade-off between predictive performance and explanatory power. Ideally, corporate or government advisers and decision-makers would like access to information from the most powerful models with the best explanatory power – in situations where they have a liability they need to understand – or to have access to someone who can understand and explain in order to convince the final decision-maker, as the explanation must be intuitively logical for the decision-maker.

Economics and technology

Gordon Moore's prediction focused on an economic scaling effect: that as computers become more widespread, the cost of manufacture decreases, sales increase, and computers continue to become more widespread. The history of digital computing has so far vindicated this truism, at a rate unprecedented outside ICT-related industries. Rapid adoption by industry of a bespoke research tool opened opportunities to academic researchers as well, which resulted in industry breakthroughs that reduced the cost of computers. Their widespread use in business, finance, other industries, academia, and government has entrenched computer modelling and simulation as a tool for analysis and investigation across all sectors, which has in turn reinforced the ubiquity of computers.

A very large injection of sustained funding from the US government during the 1950s, at a critical time in the development of electronic programmable computers, ensured the industry remained at the forefront of research and technical innovation as well as business processes. There may be lessons for funders and investors in this story of unimaginable commercial and national benefits flowing from a piece of fundamental research funded by the state (Box 10).

Economist Robert M. Solow famously remarked in 1987 that 'you can see the computer age everywhere but in the productivity statistics' (Solow, 1987). Erik Brynjolfsson (Brynjolfsson, 1993) popularised this notion as 'the productivity paradox of information technology' – the discrepancy between increasing investment in information technology and a decline in total factor productivity in the US from the 1970s to the 1990s. Economist Robert J. Gordon has argued for well over a decade that technology at large is subject to diminishing returns as a productivity lever and that ICT in particular is over-hyped. Gordon (Gordon, 2000, Gordon, 2012) declared that 'computers and the Internet fall short' in comparison to the innovations of the Second Industrial Revolution (1860 to 1900), because the effects of their adoption and market penetration are apparently not seen in standard productivity measures. Furthermore, Gordon (Gordon, 2000) argued that 'computers are actually less pervasive in the economy than is generally thought, because some tasks are resistant to replacement of human beings by computers'. (Conspicuously failing to anticipate the growing availability of self-service check-outs and automatic ticketing, he noted grocery cashiers, grocery baggers, and parking lot attendants as some of 'many other services [that] require in-person contact between an object and the practitioner'.)

Perhaps the invisibility of modelling and simulation blinded commentators like Gordon to its near-ubiquity across all areas of research and industry over the last several decades (including in economics and financial markets), or perhaps he simply does not recognise it as a pervasive component of ICT. He argues that 'the heaviest uses of computers are in industries that provide mainly or entirely intermediate goods', discounting their widespread use at the time in such diverse products as automobile antilock braking systems, mobile telephones (even in a pre-smartphone age), cinema, printer cartridges, appliances, satellites, GPS, and communications equipment. Also, as Richard Lipsey and colleagues (Lipsey et al., 2005) have observed, some of the most important innovations generated by ICT have been service or process innovations rather than product

innovation, and hence will be opaque to standard measures of total factor productivity. Lipsey et al. argue that long-term economic growth is largely driven by general purpose technologies like electricity infrastructure and ICT, and that there are few goods and services in the 21st century that are not made with the aid of computers at some stage during their production and manufacture. 'New ICTs have already revolutionized society and will continue to do so well into the 21st century,' they wrote. 'Some of these are minor whereas others are transforming, such as globalization and its many ramifications, the dramatic changes in the organization of firms, the end of mass production and its associated labour and management requirements, the alternations in the political power structure, the emergence of the civil society and its effects on the conduct of international negotiations' (Lipsey et al., 2005).

Recognising an area of market failure in the nexus between the potentially critical economic importance of large-scale collaborative research infrastructure and its large up-front and continuing expense, two significant recent Australian Government reports, the 2011 *Strategic roadmap for Australian research infrastructure* and the 2012 *National Research Investment Plan*, have acknowledged the need for ongoing, holistic funding for large-scale collaborative research infrastructure, including high-performance computers (DIISRTE, 2011) (DIISRTE, 2012). The development of two of Australia's three petascale computers, the Pawsey supercomputer in Perth and Canberra's National Computational Infrastructure (NCI), was possible only with the injection of significant public funding for capital costs via the Australian government's Super Science Initiative in 2008. Other significant public funding also comes via collaborations between Australian universities and other publicly funded research agencies, in particular CSIRO. The third Australian petascale computer, the Victorian Life Sciences Computational Initiative (VLSCI), has been funded by the Victorian Government and a number of research organisations, in partnership with IBM. It remains the biggest supercomputer facility devoted to life sciences in the world. All three facilities are available for industrial as well as academic research.

Other effects and limits

Models can be such powerful heuristic tools that it can be easy to ignore their limitations. These limitations include:

- *error*, including the multiplication of rounding and truncation errors, poor choice of parameters, poor choice of model type, bad or inaccurate data
- *circularity* For example, a criticism of some economic models is that they embed the assumptions of the modeller as fundamental inputs, and fail to validate empirically.
- *legibility* In any model and simulation, the modeller must try to optimise the balance between predictive performance and explanatory power. This always results in a trade-off.
- *ethical implications*. Some examples include:
 - decreased need to use human and animal subjects in medical testing – therefore if models can be used, suffering will be reduced
 - improved ability to track disease, consequences of natural disasters, warfare etc.

Digital computers are powerful tools for change, and are resource-heavy to produce and run. Any powerful, near-ubiquitous technology will have effects that can be read as positive and negative.

- *Ethical implications* Some examples include
 - Electronic social networking sites, sites for online shopping and search engines are associated with poorly regulated data collection. Users may unwittingly trade their privacy and security for a 'free' service.
 - On the other hand, electronic social networking is a powerful enabler of free speech and democracy, as evinced by the Arab Spring, and by organisations like WikiLeaks which support and empower whistleblowers.

- The two above impacts may be represented as positive or negative, depending on all sorts of factors, including business model, patterns of use, sector, and short-term outcomes.
- Environmental impacts of ICT are high and can fall unevenly on the poorest and most vulnerable (Box 11).
- *Environmental and resource implications* Data centres are notoriously energy-hungry, and computer components may be made from toxic material, environmentally expensive to mine and dispose of. On the other hand, with widespread use of increasingly sophisticated modelling and simulation tools, building prototypes will become increasingly unnecessary. (Box 11). Obsolescence can also magnify harmful environmental impacts, as the product life of computers shortens.
- *Obsolescence* The rapid progress in chip technology, and other phenomena related to Moore's Law's predictions, can result in the rapid obsolescence or redundancy of antecedent technologies. This product turnover can have implications for data and hardware security and survivability, as well as affecting operations. Clever software construction with backward compatibility will mitigate these effects, but legacy programs will run into problems eventually.

Box 11. The real costs of ICT

Historian of science Nathan Ensmenger (Ensmenger, 2013) has explored the environmental consequences of electronic digital computing in a wide-ranging discussion of the ramifications of the material production and distribution processes fundamental to computer technology. In tracing 'the global life cycle of a typical laptop computer or cell phone from its material origins in rare earth element mines in Africa and South America, to its manufacture and assembly in the factory cities of China, through its transportation and distribution to retail stores and households across America, and finally to its eventual disposal in places like the slums of Agbogbloshie, Ghana', Ensmenger reveals that 'the computer industry is built on more than just abstractions, algorithms, and information'. He elaborated that whether 'studying the toxic by-products of semiconductor manufacture, the enormous amounts of energy and water consumed daily by massive Google and Facebook server farms, or the use of child labor in the "computer graveyards" of the developing world', we should acknowledge 'that computer power comes at a cost and that the physical infrastructure that enables their virtual interactions are resource-intensive, pollution-producing, and potentially damaging to the environment' (See also (Hirsch, 2013)).

In 2002, according to the UN, a single desktop computer 'required 240 kilograms of fossil fuels, 22 kilograms of chemicals, and 1,500 kilograms of water – and that does not include the human labor involved' (Williams et al., 2002). Massive data-driven companies and services whose business models rely on the internet (like Google, Amazon, and Facebook) have grown very rapidly in the period since. These companies have required an enormous investment in new energy-production and heat-dissipation infrastructure. Ensmenger cited New York Times investigative journalist James Glanz, who in 2012 observed that the 'collective global demand for power for digital data centers accounts for the output of roughly 30 nuclear power plants ... with server farms in the United States accounting for as much as one-third of this total load (Glanz, 2012) in (Ensmenger, 2013).

Summary

In 2010, Bill Gates observed that improved software modelling is the key to beginning to solve 'many hard problems', including nuclear power and the spread of disease (Fried, 2010, Glanz, 2012). Greater processing capacity and speed of computers will continue to transform science, research, technology and manufacturing. But as Gates observed, in addition to raw power, off-the-shelf modelling tools and data packages are central to improving the capacity of researchers to test hypotheses and generate data about the world. This is particularly the case for the long tail of researchers whose work does not need the processing power of a petascale computer – but for whom the cost and time of basic modelling impose significant limits.

In considering the rise of digital computing, modelling and simulation in the late 20th and early 21st century, this paper addresses broad themes in the history of technology including:

- the relationship between science, engineering and technology
- technological innovation as driving or responding to need or fashion
- patterns of technology transfer, adoption and adaptation
- economics and technology
- the roles of government and industry

Digital computing, computer simulation and modelling (sometimes known as the third paradigm, or computational science) is a pervasive, general purpose technology, which will continue to affect Australia's security, cultural, democratic, social and economic systems. For instance, computers can model the likely effects of changes in climate on vulnerable coastal environments, and the economic, social, and ecological implications of these changes, as well as testing options for remediation and the costs and benefits of different kinds of development. The challenges of managing food, health, population, urban design, energy, biodiversity, water quality, greenhouse gas balance and energy are particularly acute in a sparsely populated country like Australia, with our added challenges of large arid and semi-arid regions isolated from urban infrastructure, our remote industries, and a variable climate; they are made more so with the hotter, drier climate threatened in many models. A reduction in arable land will put pressure on other uses, such as those of the mineral industry, and on assets such as Australia's unique biodiversity, as well as threatening food security.

Computer modelling and simulation can offer scenarios and options for Australia given a variety of policy settings and climate, population, economic and technological trajectories. Some of these innovations are possible with current computer power, but the next generation of supercomputers is critical to improving prediction in complex but important areas of research like climate and meteorology, oceanography, fluid dynamics, and energy. However, while some disciplines and industries will continue to use all available processing power and speed, other intellectual and technological trends in the history of computing resulting in, for example, better targeted software, improved networking, and increasingly sophisticated data analytics, have partly decoupled improvements in modelling from raw computer power.

Computer simulations are part of the construction and validation of scientific knowledge. They are often the only access we have to explanations for phenomena which are large and complex, or for which data are scarce. Therefore decision-makers need mechanisms to evaluate the dependability of data arising from simulations.

Computer models and simulations are powerful and pervasive cognitive amplifiers, nearly invisible general purpose technologies that continue to transform our security, cultural, democratic, social, and economic systems.

Anticipation of new developments in science and technology

The steady advance of electronic technology is predicted by Moore's Law – Intel co-founder Gordon Moore's observation in 1965 that, over the history of computing hardware, the number of transistors on integrated circuits had doubled approximately every two years. Moore's Law, its corollaries, and other similar laws or trends also lay down the rules for a technological arms race. Such predictions provide both a degree of predictive power and a self-fulfilling prophecy for improvements in computer processing, as the chip industry strives to continue to fulfil Moore's prediction (Kanellos, 2003).

While supercomputers have improved steadily over the last three decades, assisted by Moore's Law-like improvements in chip manufacture and accompanying economic scaling, there are physical restrictions, most tellingly those governing energy efficiency and cost. To make the transition from petascale to exascale supercomputers, machines will need to be much more energy efficient, more

error-tolerant, and will require programming innovations. It also seems likely that chip manufacturers may be reaching the practical limits of Moore's Law, as transistors approach what may be some basic barrier to further reducing size, or alternatively the point at which the costs of research and development outstrip the reduction in cost of smaller chips. Fundamental shifts in approach may be called for, as for example, breakthroughs in quantum computing (Service, 2012).

The history of digital computation in Australia – suggestive of opportunities lost and other innovations capitalised on – demonstrates that trying to predict the trajectory of a particular innovation is a fraught business. Endogenous and exogenous factors are both important in achieving and maintaining commercial success for a given technology (cf. (Yost, 2013)). For example, despite its world-equalling innovation in the development of CSIRAC (endogenous), CSIRO discontinued the program in 1954 in response to the development overseas of solid-state devices like the transistor which replaced vacuum tube technology (exogenous). These new technologies allowed smaller, faster, more reliable computers. CSIRAC's designer Trevor Pearcey considered that Australia had lost an opportunity to capitalise on CSIRO's early leadership (endogenous) (Pearcey, 1988). But computer historian Peter Thorne suggests that the growth of a globally significant hardware industry in Australia was unlikely, given the export restrictions and cost caused by Australia's physical isolation from the largest markets (both endogenous and exogenous), and the small internal market for computer hardware in Australia in the 1950s (endogenous). IBM's huge market share by the end of the 1950s perhaps vindicates this view. Australia's advantage was not completely squandered: CSIRO's early experiment with CSIRAC, and its use into the 1960s, may have contributed significantly to what Thorne describes as Australia's ongoing strengths in software development and modelling (endogenous) (CSIRO, 2011, CSIROpedia, 2011, Johnson, 2001) (see Box 4).

Technological uncertainty, risk assessment and communication, and policy development

Improvements in processing power and concomitant sophistication in simulation and modelling can improve the calculation of risk and uncertainty, and the implications of these calculations across a range of disciplines and industries, including modelling the effects of different technology choices.

Computer simulation may permit modelling complex social and economic scenarios for improved public policy outcomes. However, effective use of such models will only be possible if modellers and policymakers alike have some understanding of their limits.

Timescales to influence adoption and use

Modelling and simulation in some form are already ubiquitous in the research sector and widely used in government and many industries – but their uptake could be encouraged across all sectors. However, there is no point having a powerful tool if you do not know how to use it: skill development is essential to capitalise on investment.

Computer modelling and simulation pervade the municipal and domestic spheres as well and increasingly determine our leisure activities, including how and when we socialise (Table 1). Given the ubiquity of computer modelling and simulation in the research sector and industry, policymakers rely on the results whether they know it or not. And even some forms of policymaking by popular opinion are governed by models in the form of opinion polls, which model the views of the nation, or particular sectors. Operations research, which is significant in the defence forces, business, financial markets, and any fields where decision-making is important, relies on computer modelling and simulation. Every accountant or undergraduate who uses an electronic spreadsheet to understand his or her data is modelling (Table 1).

Increasingly there are opportunities for public sector agencies to model the effects of social policies, but such opportunities would require governments to rethink policy design from idea to implementation. There are also skills barriers – public sector workers and researchers may lack the requisite ICT and statistical ability to design and analyse social policy simulations, and then

communicate their results to decision-makers and the general public. This is not a new problem or a problem exclusive to ICT, but that does not lessen its relevance.

Opportunities, barriers and determining factors for new or different uses of modern ICT across in Australia's security, cultural, democratic, social and economic systems

While ICT offers unprecedented opportunities to improve business and public policy outcomes, there are physical, economic, and skills barriers to the widespread adoption of modelling and simulation. Most of these can be overcome. Issues of public trust and understanding may be harder to deal with.

Despite the potential benefits, public perceptions of the reliability of data from modelling and simulation are confused. There may be confusion in the community about what counts as real evidence, as well as concern about the limits of an investigative technique (modelling and simulation) that by its nature cannot replicate reality exactly – and indeed would be useless if it did (for example, see Borges' 'Del rigor en la ciencia' on the ineffectiveness of exactitude in modelling – Box 12).

To some extent, there may be a naïve 'real-world' bias at work here. The results of computer simulations might be perceived as less real than experiments – experiments appear to connect with the real world; computer models do not. It may be that public trust in science, so far as it goes, is based on science being essentially experimental in method (breaking down Gray's four paradigms of scientific progress). If so, public trust in science may not persist if the scientific method shifts to be more model/simulation-oriented, or even predominantly so. As complex phenomena are modelled and simulated by increasingly sophisticated programs on more powerful machines, scientific processes may become ever more opaque to non-specialists. Lay people may also be wary of experiments performed *in silico* rather than in the world, failing to comprehend that data generated from simulated scenarios can produce accurate representations of natural systems. Trust or lack of trust in certain forms and presentations of information may skew risk behaviour. These factors may lead to an increasing distrust of science and scientists, a phenomenon already observable in popular objections to climate change science, for instance. One could attack this problem from both directions, first by emphasising the degree to which 'real world' experiments are not necessarily ecologically valid, and second, by pointing out that real world observations are crucial to success in modelling (Figures 1, 3, 4).

As well as skill and understanding barriers, there may be a standards barrier: lack of standards or poor standards in modelling, simulation, and analysis software may impede the ability of policymakers to assess whether a model will produce valid results, and how to interpret the results. Public trust in outcomes may come with increased understanding and improved standards.

Box 12. On rigour in science

'In that Empire, the Art of Cartography attained such Perfection that the map of a single Province occupied the entirety of a City, and the map of the Empire, the entirety of a Province. In time, those Unconscionable Maps no longer satisfied, and the Cartographers Guilds struck a Map of the Empire whose size was that of the Empire, and which coincided point for point with it. The following Generations, who were not so fond of the Study of Cartography as their Forebears had been, saw that that vast map was Useless, and not without some Pitilessness was it, that they delivered it up to the Inclemencies of Sun and Winters. In the Deserts of the West, still today, there are Tattered Ruins of that Map, inhabited by Animals and Beggars; in all the Land there is no other Relic of the Disciplines of Geography.'

Jorge Luis Borges, *On exactitude in science* (Borges, 1999)

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