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Create Change

July 2019

Policy Futures

Regulating the new economy

Artificial Intelligence

Synthetic Biology

Nanotechnology

Circular Economy

emerging technologies and innovations | implications for policy makers and regulators

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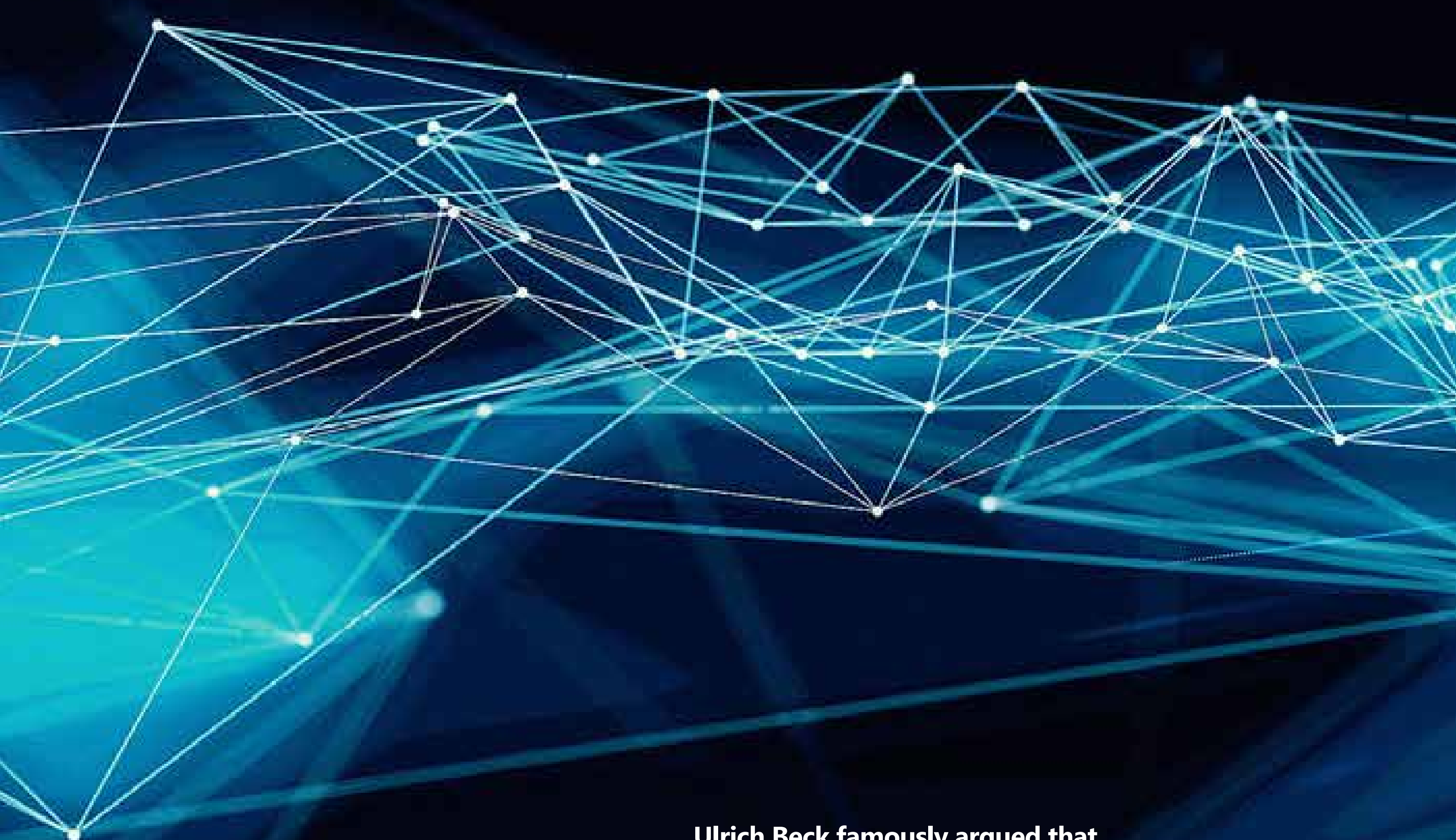
Content

Part I:
Through the Policy Lens



Ulrich Beck famously argued that we live in a 'risk society', defined as "a phase of development of modern society in which the social, political, ecological and individual risks created by the momentum of innovation increasingly elude the control and protective institutions of industrial society."[1]

"… we have learnt — often the hard way — that different social and cultural contexts produce different attitudes towards new technologies. These differences matter because 'risk' and 'uncertainty' are not objective and measurable: they are socially constructed and negotiated through political processes. … Frontier sciences raise complex questions about people, place, politics, science, technology and society, which demand thoughtful and rigorous responses." (Mitter & Hussey, 2019)[2]

Executive Summary

We live in an era of near unprecedented technological change, perhaps rivalled only by the industrial revolution of the eighteenth and nineteenth centuries. Yet the experience of the past, if anything, serves to highlight the potentially pernicious social and economic consequences of rapid change, especially if poorly regulated. It was the poor conditions of workers facing rapid industrialisation in nineteenth century Manchester that led Engels to coin the phrase 'social murder' and while this represents the thin end of the wedge, it nonetheless serves as a reminder of why rapid innovation and responsible regulation must go hand in hand.

Even if emerging technologies do not pose existential risks[i] to humans, many of them may alter the fabric of societies through their social, political, environmental or economic impacts. Indeed, the impacts of many emerging technologies will hopefully be positive and their implementation will offer solutions for various societal challenges. However, it is necessary to approach this process in such a way that socio-economic collateral damage is minimised, which is precisely where regulation (amongst other policy tools) is essential.

There are several characteristics of emerging technologies which represent key departures from past technologies and experience. The growing scientific prowess of humanity has brought us to a threshold of being able to enact widespread, fundamental, and potentially irreversible changes to humankind and the environment around us: our sustained use of fossil fuels has seen us alter the planet's climate; gene drives can propagate a suite of particular genes through a species, irreversibly altering the basic nature of a living organism or, indeed, an entire population of organisms; while artificial intelligence (AI) has the potential to fundamentally challenge some of the core aspects of what it means to be human. Beyond this, the scale, irreversibility, and magnitude of some emerging technologies has brought the concept of existential risk to the forefront in a way not considered since the invention of nuclear weapons. Fears of rogue AI in the manner of *The Matrix* or *Terminator* may be overblown but it is certainly worth considering whether some technologies may pose risks to humanity at large or challenge the extent to which humans are willing to cede decision making and autonomy to machines.

The rationale for this Think Piece rests on the need to account for three challenges in the way we design, deliver, review and reform regulation in the coming years: first, emerging technologies today may be fundamentally different from the past in terms of their impacts and risk profile; second, this risk profile encompasses a range of impacts from existential[i] to individual, and ontological[ii] to economic; and third, regulators must manage these risks in the context of the situational difficulties outlined below.

To support regulators in this task, in Part I we have identified four 'Key features of new and emerging innovation' that interface with contemporary global settings and which are particularly challenging for regulators. The first two – 'splitting' and 'convergence' – relate to the nature of new technologies, while the latter two – 'divergence' and 'new value' – relate to the way technologies are likely to interact with a globalised political economy.

We have developed a 'Technology Pipeline', which we apply in Part II to allow regulators to identify the drivers, enablers, inputs, processes and outputs from new technologies and concepts. We hope the

[i] Existential risks are those threats which endanger the well-being of humanity as a whole.

[ii] Ontological risks are threats to individuals' sense of well-being and security. Even absent of threats to physical security or livelihood, rapid change can lead to ontological risk and experiences of insecurity.

pipeline will provide definitional clarity for each of the innovations under discussion. This clarity is necessary due to the considerable confusion, misunderstanding and 'hype' around these technologies which can lead to obfuscation about the potential benefits they offer, and the risks they pose. We also hope the analytical framework offered by the pipeline might help regulators to identify where and when new regulation may need to be developed – or much more likely, where existing regulatory arrangements may need to be reformed – over the coming years. The pipeline is not the first of its kind, but we believe it usefully disentangles many of the features of new technologies and innovations which are often and unhelpfully conflated in other schemas.

Key features of new and emerging innovation

Technology splitting

The potential for technology to advance so rapidly that it outstrips the social and economic frameworks that manage it is well documented and has arguably taken place for as long as humans have innovated. Indeed, there is considerable evidence that the spread of iron caused widespread dislocation in Bronze Age Europe and the advent of gunpowder played a key role in undermining the entire socio-political basis of Feudal Europe. This capacity for innovation to proceed more rapidly than regulatory frameworks is known as the '**pacing problem**' and there has been considerable work on ideas like '**anticipatory regulation**' which seeks to ameliorate its negative effects.

However, it is not merely the pace at which contemporary technology changes but its capacity to migrate across applications and into new sectors that is challenging regulators. We have termed this phenomena technology splitting and defined it as the capacity for a technology to rapidly proliferate into new applications in ways that are hard to anticipate. This splitting effect exacerbates the pacing problem as, not only do regulators have to manage linear changes in technology within their bailiwick, but they must also be aware of new (and sometimes surprising) technologies, potentially leaping into their sector.

A key example of this phenomena is the potential spread of CRISPR-based synthetic biology which was initially envisaged for use in a small suite of applications in the heath and agriculture sectors, but whose impact is being felt across a much wider range of sectors, for example in environmental conservation. This incursion of gene technology into the sectors managed by previously uninvolved regulators has created new and urgent needs for collaboration, coordination and new skill development.

Technology convergence

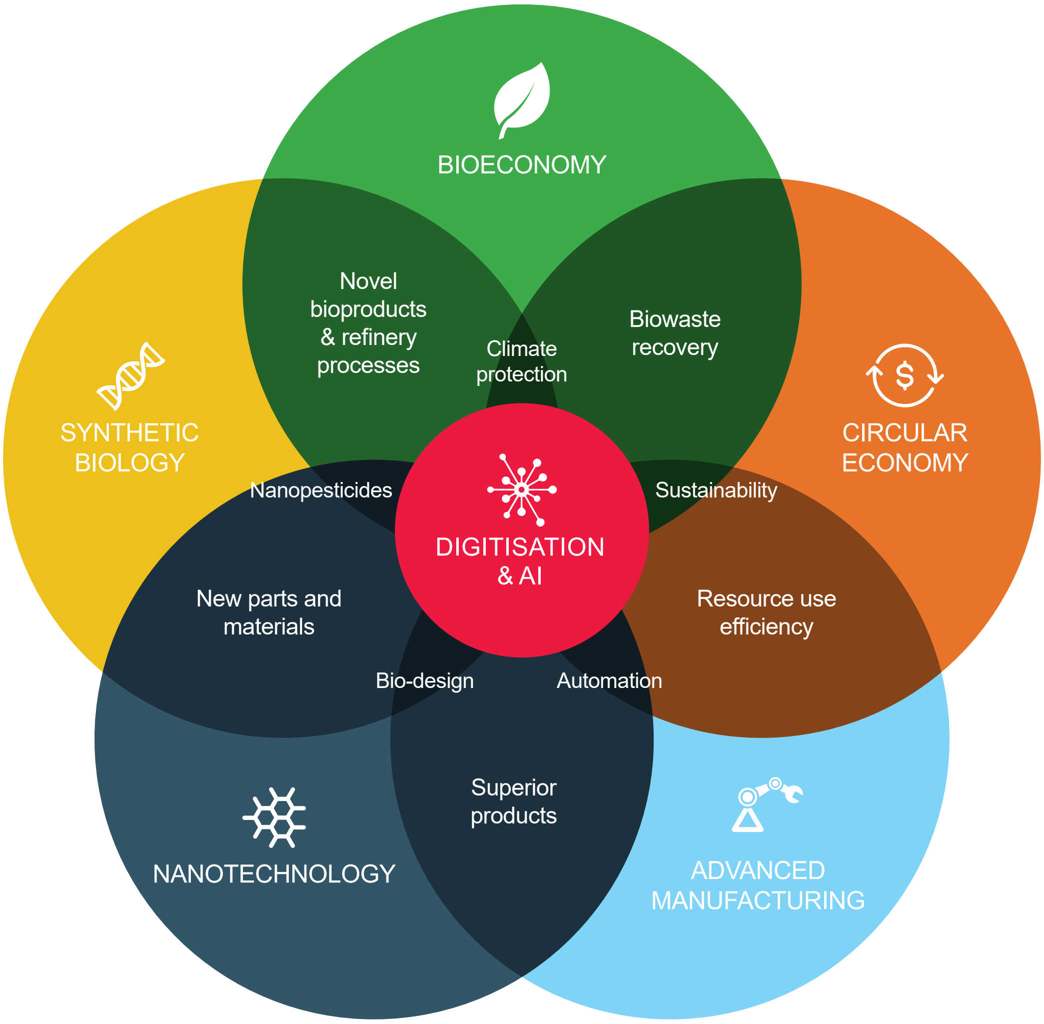
Integral to the nature of innovation is its capacity to feed off, and combine, with other technologies. This is not a new phenomenon: an object such as a spear may seem non-composite but its origins lie in the realisation that a hand-axe may be made more lethal by attaching it to a long stick. This is an example of what we term '**piggybacking**' – where two technologies are combined to better accomplish an existing task or to otherwise increase the efficiency of one or both technologies.

Historically, the key to piggybacking has been its linearity, insomuch as the combination of technologies did not fundamentally change the nature of the technology or its application. Using the example of the spear, it is a better version of a pointed rock but still accomplishes fundamentally the same tasks. The majority of innovations arising from piggybacking will be linear like the evolution of the spear or the development of driverless cars, which combine AI with existing transport technology without fundamentally changing the purpose or use of the car.

However, the more difficult challenges that regulators need to be aware of are posed by '**technology convergence**' – another form of combination yet *fundamentally different* to piggybacking. Technology convergence refers to the phenomenon whereby two previously separate technologies become combined such that they create a new technology or novel application through their interaction. In contrast to piggybacking (i.e. where the change is linear), changes due to convergence may be exponential or paradigmatic. For example, the convergence of genomics (the ability to sequence genomes comparatively quickly and in significant volumes to generate massive data sets) with advancements in artificial intelligence, has allowed us to interrogate and interpret that genetic data in a way that enables new understanding of, and responses to, genetic variation.

Relatedly, some scholars have pointed to the geopolitical implications of synthetic biology by virtue of that platform's interactions with data science and the subsequent, potential impact on a country's genetic endowment.

Figure 1. Technology and innovation convergence and splitting



"The convergence of the biological sciences and the information sciences is creating novel security concerns that impact on Australian sovereignty, both mainland and the Antarctic Territories, plant and animal health, and defence medical infrastructure. These concerns cross many traditional disciplinary and policy boundaries, an awareness of this is required and a nascent national practitioner community can develop this further." (Dixon, 2019)[3]

New economic value

New technologies have always been key drivers of vibrant and productive economies through the creation of new value and their demand for previously underexploited resources. For example, prior to the twentieth century, crude oil was a geological curiosity but the invention of the internal combustion engine made fossil fuels intensely valuable and consequently changed global geopolitics. Thus, regulators must consider new technologies not only in terms of their processes, outputs, and outcomes but also the resources they require as inputs. One form of new resource value is the monetisation of waste in the context of the circular economy and e-waste processing. In these cases, the sudden value attached to resources that would once have been thrown out or undervalued raises difficult questions about the definitions of waste, where it can be processed, whether it can be consumed (by whom and how), and indeed, whether it can be exported.

A further example of new resource value is the sudden usefulness and monetary value of otherwise prosaic goods such as data or genes. The high value of these new resources may make them vulnerable to regulatory non-compliance and when the goods are derived from individuals—such as genes and data—there are issues around the ownership, transferability and sovereignty of those 'goods' in domestic and international jurisdictions. Indeed, when approaching the economic and socio-political impacts of new resource value from emerging technologies, regulators must be prepared to think both locally and globally. Local or individual impacts will include issues such as ownership and processing of resources (e-waste recycling, technology critical element refining). However, a global focus will ensure we incorporate the impacts of emerging technologies on the international political economy of some industries. For example, a number of technology-critical elements (TCEs) may now be considered 'conflict minerals' because they have been shown to directly feed into currently-active irregular conflicts (e.g. coltan mining in the Democratic Republic of Congo). Similarly, regulators and policy makers must also be 'alive' to the *scale* of the potential changes that new technologies might catalyse. As noted above, oil was largely a geological curiosity until the internal combustion engine made it hugely valuable, but the consequence of that discovery was the fundamental shift in international politics and economics. It is highly likely that the impact of new discoveries relating to synthetic biology and artificial intelligence could also bring about such paradigm shifts.

Regulatory divergence and jurisdiction

The various socio-economic issues of emerging technology highlighted so far do not occur in a vacuum—they are even more challenging because of the globalised context in which they occur. We have identified three challenges that arise from the interaction of either technologies themselves or technology regulations within highly integrated global markets.

First, international borders today are highly permeable and many of the most valuable goods associated with new and emerging technologies, particularly those in the digital realm, are able to cross borders extremely quickly (e.g. genomic knowledge, or data). We refer to this problem as the **'speed of transfer'**.

Besides the speed of transfer, there is also the difficulty of managing technologies and goods once they cross international boundaries. In many cases the speed with which regulators have had to manage technologies has led to a disparate and *ad hoc* approach to the same technology across different jurisdictions (e.g. the regulatory differences associated with CRISPR-based gene editing between the United States (US) and the European Union (EU)). Consequently, international trade and collaboration may be hampered by a lack of inter-operability in regulations – this is not to suggest that all states must regulate the same way but that international interaction requires regulations to at least 'talk to one another' so that compliance with multiple jurisdictions can be facilitated.

In the area of data protection, at present there is a fundamental disconnect between the regulatory priorities of individual data in the US and the EU. In the former, commercial freedom and freedom of speech are favoured while in the latter, European regulators favour the rights of the consumer and citizen.[4] Similarly, tension between China and the US to dominate the semiconductor industry is a good example of where technology, geoeconomics and standard-setting intersect in the fight for market dominance. This disconnect in regulatory approaches not only affects the commercial sector but can also affect certain public goods such as medical research, cross-border crime prevention, or the stability of the international system of trade.

A related, final challenge, therefore, is the need for a coordinated and collaborative approach to the regulation of technologies at the international level. The costs imposed on businesses from operating in different regulatory environments means that '**regulatory divergence**' is now far more of an impediment to international trade than tariffs and quotas.[5] Wherever possible, therefore, regulatory divergence should be overcome through harmonisation or mutual recognition of different regulatory regimes. Yet, the high value associated with some technologies means there is a perverse economic incentive for actors to impose less stringent regulation than their competitors so as to seek a comparative advantage; through either their own technological development or by attracting high-tech companies to low regulation environments. This has already occurred with China's approach to certain gene and stem-cell technology, and there is risk of it being spread further unless a coordinated international approach is taken.

Key examples where this collaboration might be needed are: data-commerce, lethal autonomous weapons systems, and synthetic biology. Clearly, there is already considerable effort expended to achieve a degree of international harmonisation in areas of innovation, but we know from past experience that international cooperation is inherently political and time consuming, which is highly problematic given the increasingly crowded international sphere where such standards are negotiated, and given the 'pacing problem' described above.

How regulators can adapt to the new world

In many ways, the role of regulators is as it has always been: to provide an enabling environment in which businesses and communities can flourish, while simultaneously ensuring the economic, social, environmental and geopolitical risks that arise from new technologies, goods and services are identified and managed over time. Certainly, Australia's existing regulatory landscape already accounts for review, capacity building and expert elicitation, but the consequences of technology splitting, convergence and piggy-packing, combined with the pacing problem and the implications of new technologies for international trade and geopolitics, mean that regulators will need to adapt in the coming years. Such adaptation demands attention be directed towards:

a) the administrative arrangements that underpin the policy and regulatory landscape;

b) the skills, training and professional development needs of regulators; and,

c) the ways in which regulators can use new and emerging technologies in communication about, and the design, delivery, and enforcement of, new regulation.

In relation to the administrative arrangements that characterise the regulatory environment, the extent to which regulators can easily coordinate across agencies and jurisdictional boundaries will be critical to securing appropriate regulatory responses to new and emerging technologies. Such coordination would be facilitated by a greater level of permeability between agencies, opportunities to facilitate joint appointments and secondments within and between agencies and opportunities to undertake shared training and development activities which, by design, encourage cross-sectoral and cross-technology understanding.

In addition to greater coordination, the nature of the risks associated with some new technologies will require that greater autonomy and independence be afforded to regulatory agencies – separation from political and interest group pressure will be paramount; but concerningly, we have a chequered history in managing such separation. So too does the extraordinary pace of change in new technologies and the complexity within and between them, mean that mechanisms to allow for more frequent regulatory review are needed, to incorporate new knowledge and experience. Without regular reviews, anticipatory and adaptive regulation will not be possible. Relatedly, the central role of law reform commissions must be reinforced, as well as processes and mechanisms by which independent expertise, industry, community and consumer experience, is captured.

In relation to regulatory capacity, there will almost certainly be a need to build regulators' knowledge of new and emerging science and associated technologies, with 'continuous learning' even more important in future regulatory teams. The transboundary nature of the risks associated with new technologies also means that deeper understanding of the international dimensions of new technologies is needed, notably the geopolitical and trade implications of new technologies and their myriad applications. Relatedly, the governing boards of many regulators will also need to have sufficient capacity as to be able to determine their 'risk tolerance' as new technologies and applications emerge, and as societal expectations evolve.

Arguably, there is an important role for universities and research institutes in this domain, perhaps most obviously through the design and delivery of training opportunities that 'bring regulators on the research and development (R&D) journey'. To some extent such interaction is afforded by Cooperative Research Centres and Centres of Excellence funded by the Australian Research Council, but often those projects are so far down the innovation pipeline that regulators have limited opportunity to plan ahead, or limited scope to consider cross-technology, cross-sector or cross-jurisdictional implications.

Decades of regulatory theory have shown the futility of regulation when it is misunderstood, impossible to implement or enforce, or is considered illogical or 'unfair' and thus illegitimate by affected parties. Aside from employing traditional tools and strategies to account for these possibilities, there is also scope for regulators to use new and emerging technologies to improve their own business practice. For example, the 'Internet of Things' (sensors, networks and analytics) is now in use by agencies dealing with public safety, food safety, environmental pollution, traffic management, and energy and water management, amongst many others.[6] The use of new technologies in regulatory delivery has the potential to offer greater transparency and accountability on regulatory oversight, as well as potentially deliver more cost-effective approaches to enforcement and compliance.

Furthermore, regulators' interface with those who are subject to, or affected by, regulation can also be enhanced by new communication channels such as social media – although the scrutiny and subsequent pressure placed on regulators through social media is an issue in its own right which requires new responses. Additionally, there needs to be active engagement with the diverse communities of Australia. For example, regulators and policy makers must consult with Aboriginal and Torres Strait Islander peoples to understand the impact that innovative technologies have on their communities. Combined, these opportunities require regulators to be more innovative and proactive than they might have been in the past, but there is a clear need for 'safe spaces' in which regulators can pilot new approaches to regulatory design and delivery. Similarly, Australia's federal system should be exploited to ensure those states/territories with less capacity are enabled to learn from those with more capacity for innovation.

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Recommending further reading—Technologies Regulation in General

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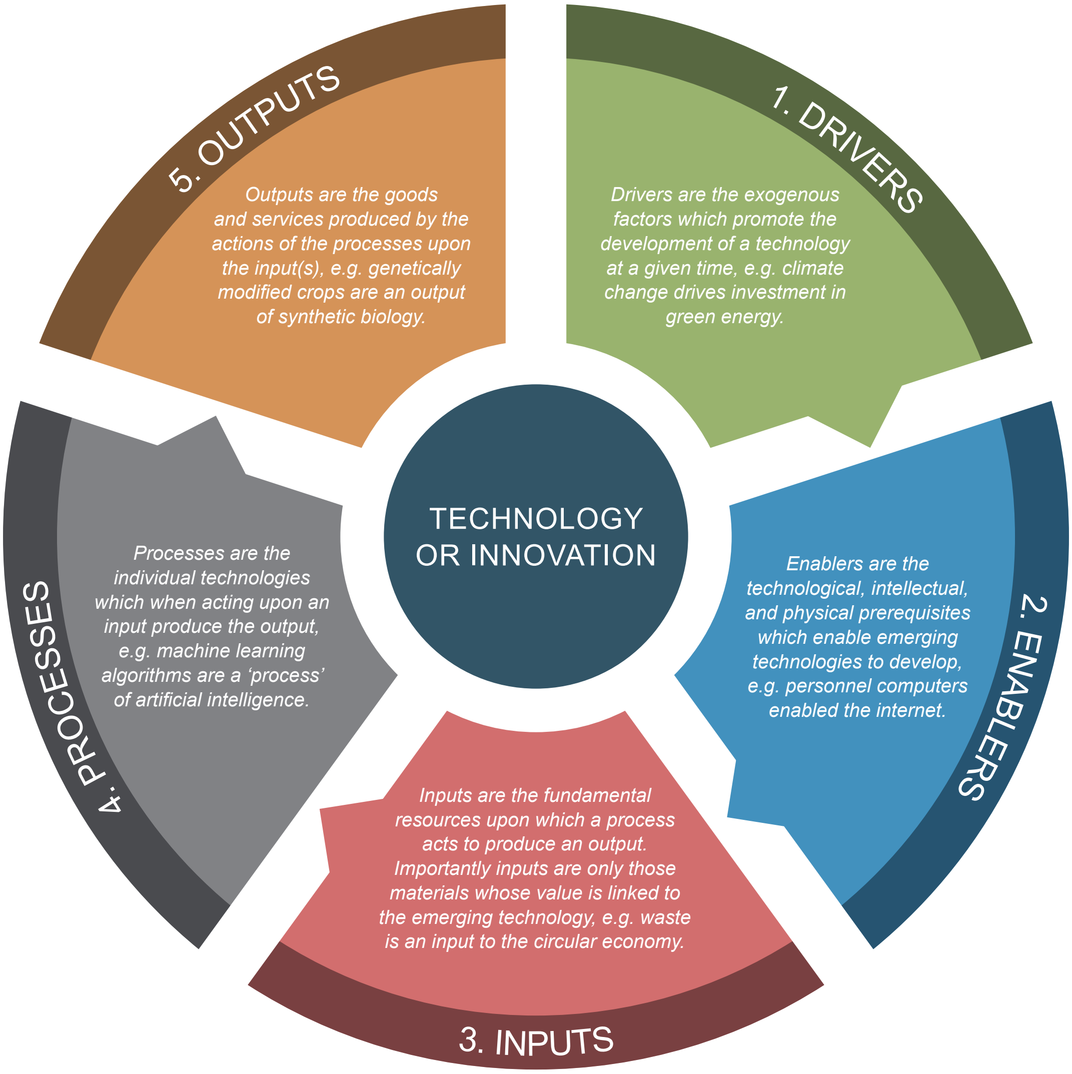
Figure 2. Technology and innovation pipeline



Analytical Framework

The technology pipeline

A key contribution of this report is the technology pipeline shown in **Figure 2**. Our goal in developing this pipeline has been not only to seek definitional clarity but to illuminate how the discrete elements of emerging innovations are linked to create a novel socio-economic pathway from drivers to outputs. Importantly (and concerningly) for regulators, emerging technologies are often viewed as bubbles in which the technology is synonymous with the process (e.g. algorithms in AI) or a product (e.g. a driverless car).

It is our view that this bubble needs bursting – emerging innovations can only be defined, understood, and, vitally, regulated if they are viewed holistically as a socio-economic pathway linking drivers, enablers, inputs, processes, and outputs. In this report we apply this analytical framework to four examples – **artificial intelligence, synthetic biology, nanotechnology** and **circular economy** and show how this approach can assist regulators in identifying their potential risks, needs, and roles at each stage of the pipeline. It is our hope that this holistic approach provides additional clarity and simplicity for regulators in dealing with new innovation in their challenging global environment.

Drivers

The 'why' behind innovation is often lost in the excitement of technologies themselves and forgotten is the truth that innovation is fundamentally driven by human needs and desires. Some of these drivers are permanent and universal (security, shelter, sustenance, convenience, etc.) while others are transient, and appear and disappear over time. It is these latter exogenous drivers which through their effects on human needs fuel the search for solutions (i.e. innovation) and consequently, it is with these drivers that the technology pipeline will be most interested.

Fundamentally, understanding drivers is a question of understanding why humans are willing to expend the necessary effort, or bear the necessary costs, to develop new innovations. For example, the development of agriculture came at considerable cost to human health (high starch diets, zoonotic diseases, physical burden to subsistence farmers) and the billions poured into artificial intelligence are even more inexplicable unless there is some reason why these innovations are, at a particular time, an attractive option.

Thus, through a focus on 'drivers', we explore the exogenous factors that created a need or an opening for this innovation at this time. For regulators, understanding the drivers behind innovations helps to explain why investment is an attractive option and is vital to making sense of the perceived benefits of technology. If ignored, there is the danger that innovation may be pursued with regulators being unable to make informed cost-benefit decisions.

Enablers

Humans have long desired to fly; in the fifteenth century, Leonardo Da Vinci famously developed sketches of an 'aerial screw', a sort of proto-helicopter, but lacking a means to power it and a thorough understanding of aerodynamics it was impossible to realise that dream during his time. What this illustrates is that the desire for an innovation to fulfil a driver is not enough; there must be technological, intellectual, and physical prerequisites in place that enable that technology to emerge at the given time. Isaac Newton famously discussed the notion of 'standing on the shoulders of giants' and in the context of technology those shoulders can be thought of as the enablers.

A good example in a modern context is the growth of genomic databases and profiling which has only been possible due to exponential increases in computing power through the second half of the twentieth century. Without these increases in computing power the size of these databases would simply be too great for computers to efficiently manage them.

Thus, enablers are the components and technologies that make further technology possible. They may be tangible, such as hardware and finance or socio-political such as policies, frameworks, and legislation. Understanding 'enablers' is particularly important for regulators because it is often the case that 'enablers' are the focus of current research and development and thus with a focus on them, regulators may potentially be able better to foresee future technologies ahead of time.

Inputs

Inputs may be considered the raw resources or 'ingredients' which feed into a given emerging technology and upon which its output is reliant. Most technologies require a range of inputs from the prosaic (e.g. electricity) to the specific (e.g. data). Crucially, here we define inputs as only the latter; those resources critical to the emerging technology and whose value is linked to the existence of the technology in question. For instance, an input such as crude oil is merely a bio-geological curiosity in the absence of a combustion engine (enabler), which converts it via internal or external combustion (process) into useful mechanical energy (output). More recently, a number of chemical elements used in computing, communications and clean production technologies, such as rare earth and platinum group elements have become 'technology-critical elements'. Inputs need not be physical however – big data is the key input fed into artificial intelligence systems. Understanding inputs is vital because of their important economic interactions which are likely to have socio-economic outcomes of which regulators need to be aware.

Processes

While enablers are those innovations which allow technologies to emerge in the first place, processes are those innovations by which the output of a technology is created. Like all innovation, the process involves a novel technology (e.g. CRISPR gene editing), multiple novel technologies (e.g. synthetic biology) or simply a new way and means of creating an output (e.g. 'sharing' services like

Uber and Airbnb). Often the emerging technology as a whole, for example artificial intelligence, is thought of as synonymous with the technologies encompassed in the process. This is only partially true, as the inputs, and enablers must be considered vital components of any emerging technology and regulating responsibly must involve treating the outputs and outcomes as inseparable from the process. Processes are often the targets of regulators at present (e.g. genetic modification or biorefinery processes).

Outputs

The concept of outputs, as distinct from outcomes, is thankfully one in very common parlance in the scientific and regulatory community. Outputs may be considered the goods and services produced as a consequence of the process(es) when applied to the input(s). Outputs are key because this is the phase at which most consumers and the public will interact with emerging technologies. Critically, in addition to considering outputs in terms of individual products' impact on consumers and the environment, outputs must also be considered in terms of the interactions between different goods and services, including interactions with different sectors.

Technologies

As highlighted above, this report features four emerging technologies/innovations and unpacks them using the technology pipeline expounded upon above. Below we have briefly previewed each of these and explained why we consider them to be a future technology of critical interest to regulators.

Artificial intelligence

Artificial intelligence is everywhere; from your mobile phone, to your spam filter, through to our court systems, and military drones hovering over faraway places. All these systems are fundamentally just computer programs but what sets them apart is their ability to perform tasks traditionally associated with 'human' intelligence and to make decisions with minimal to no human input (autonomy). If this doesn't concern you already, then consider that the major input to most of these systems is information about you; from the GPS data in your phone based on your use of Google Maps™, to your search history influencing the sorts of advertisements you see. The use of AI is only set to expand in the future and so it is vital that regulators get across the issues now rather than in an *ad hoc* and *post hoc* manner.

Synthetic biology

The manipulation of biology through genetic processes is not new – humans have engaged in selective breeding to choose traits in animal and plant species for as long as we have had agriculture. Synthetic biology however represents the latest frontier in humanity's ongoing quest to manipulate the biology of organisms we exploit; a pathway which leads from Mendelian genetics and Darwinian natural selection in the late-nineteenth century, through to the Modern Genetic Synthesis of the mid-twentieth century, and then to advances in genetic engineering in the latter twentieth century. At its core, synthetic biology is about the synthesis (creation) of new biology rather than simply the manipulation of existing patterns of variation (breeding) and this is what makes it simultaneously so exciting and yet also so risky. In terms of positive impacts, synthetic biology may allow us to produce more food to feed a burgeoning population much more sustainably and efficiently than in the past; to develop renewable biofuels that don't rely on foodcrops; and to conserve species and, indeed, entire ecosystems, in the face of mass extinction, biodiversity loss and climate change. However these benefits must be weighted against the truly profound departure that synthetic biology represents when compared to conventional genetic modification (GM) approaches. Humans are now able to interfere with the fundamental building blocks of life and this requires serious practical and ethical consideration from scientists, regulators and the broader population.

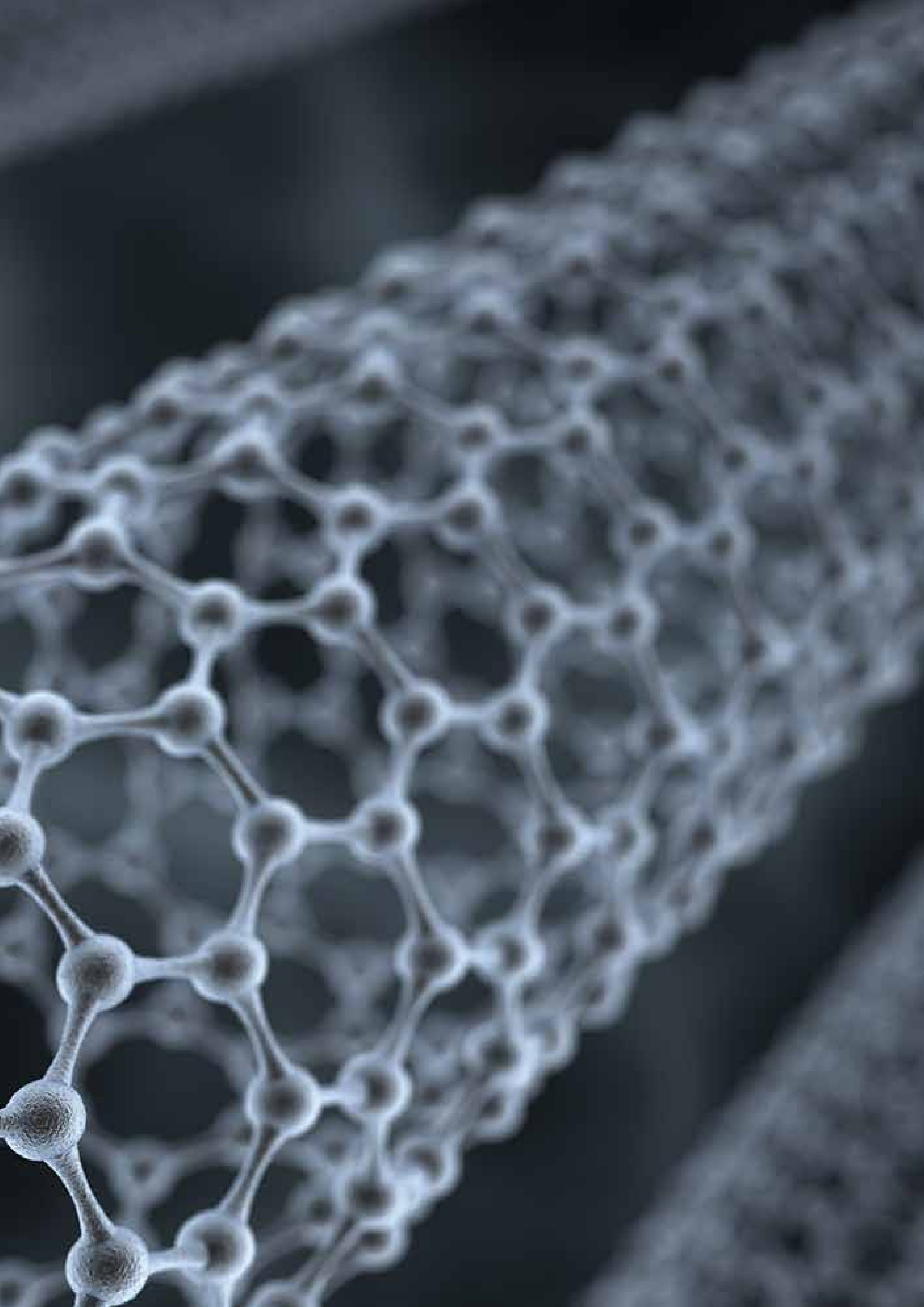
Nanotechnology

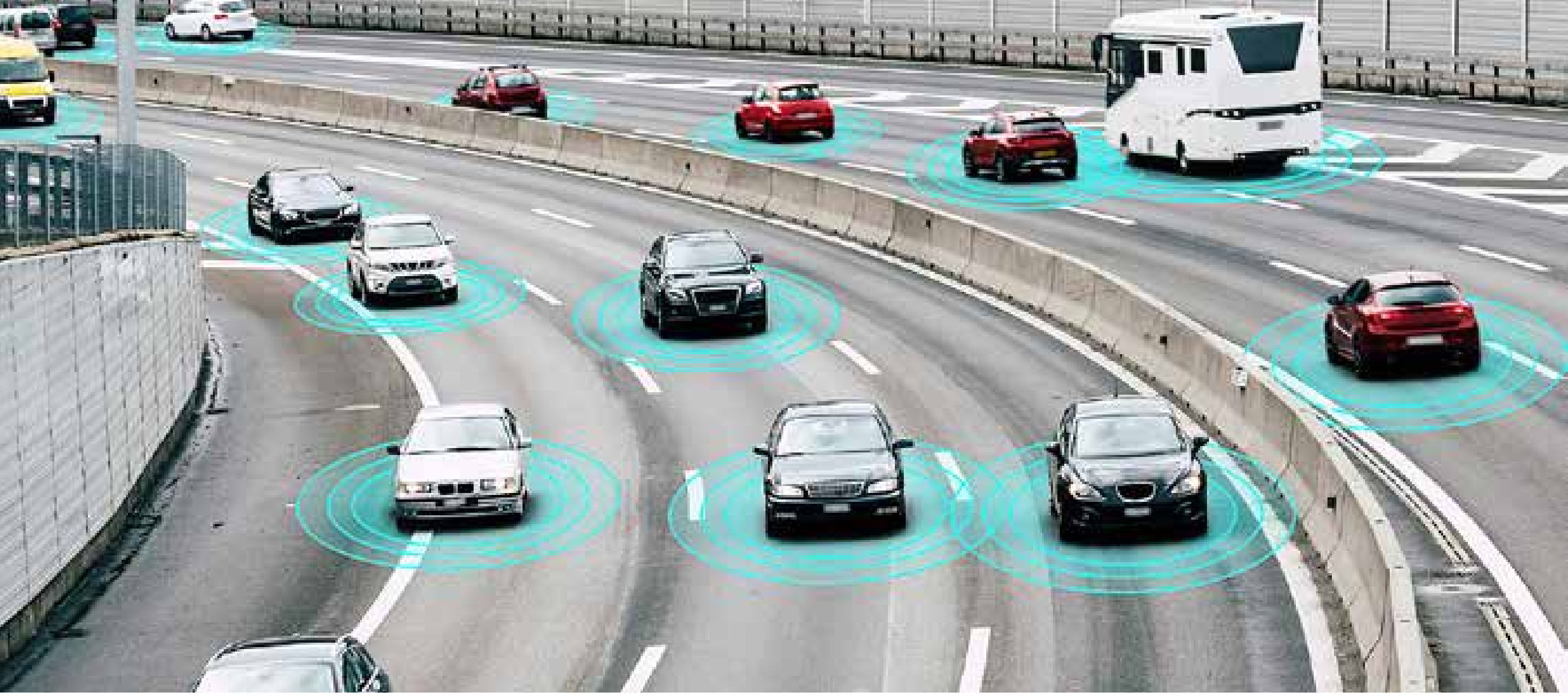
Both synthetic biology and nanotechnology share a fundamental difference to artificial intelligence, in that they act in the physical rather than the digital sphere. Like synthetic biology, nanotechnology offers great potential benefits to the physical world: its development of advanced materials can be used to improve product quality and lifespan and thus reduce waste; its enabling of quantum computer development can advance artificial intelligence systems; its production of safer chemicals, such as bio-pesticides, can improve both ecosystem and human health; and its applications in defence and aerospace can offer potentially unimaginable advances in these sectors. And yet, the relative irreversibility of unforeseen and adverse consequences to the physical world necessitates an even more cautionary regulatory approach; one that must respond faster than the companies who would be willing to exploit it for profits before the harm to the environment or society might occur.

Circular economy

The current global economic landscape has traditionally been at loggerheads with efforts to conserve the natural environment. However, the destruction and depletion of the fundamental resources that underpin economic prosperity – forests, marine ecosystems, minerals, coal and oil, soil, water and air – is now seeing yesterday's credit turned into today's debt. The circular economy seeks to close the loop on production and consumption cycles, by designing out waste and ensuring resources are continually cycled back into production. This concept is now recognised as an essential but critical challenge that must be met to ensure economic development for tomorrow.

Part II: Unpacking Innovation





As you enter your driverless vehicle, your Chatbot reminds you to pick up milk. Your milk can be traced through its supply chain back to the farm where a robot milked the cow. The milk contains genetically engineered enzymes that were designed by predictive computer software to improve your health. Welcome to now, or at least, very soon from now …

Artificial Intelligence

Definition

"Artificial intelligence is the theory and development of computer systems able to perform tasks normally requiring human intelligence."[1]

AI-driven applications have become prosaic in our lives, whether we are aware of it or not. From credit approvals and insurance premiums to your Fitbit providing you with real-time updates on your health; and the advertising and news that appears on your feed – these are just a few things driven by the power of AI. Increasingly, computers are doing more work for us, knowing more about us, and ultimately making decisions that affect our lives.

And with that, too, comes risk.

There is an intense debate on the ethical implications and impacts of AI on society and economies, and how AI should be regulated. In part, this is due to a lack of clarity as to what constitutes AI, as our perception of 'intelligence' evolves alongside evermore sophisticated technologies. While AI may conjure up images of androids overthrowing humanity in the manner of *I, Robot* and *Terminator*, it is probably not as ominous, nor as human-like, as it sounds.

Today's AI is a technology that can adapt itself to changing circumstances based on a particular self-learning ability to produce a specific output, independent of human control. This AI relies on data-driven algorithms that look for underlying and sometimes subtle patterns to reveal new knowledge. This process, combining data mining and machine learning (ML), contrast with earlier computer algorithms which were based on human designed rigid instructions or hypothetical models.

For example, early email spam filters would deem a message as spam by matching hard-coded keywords such as 'huge sale' to email content manually, or if sender emails were not in your contact list. Unsurprisingly, often valid emails might end up in your spam box, and unsolicited marketers would change email content to avoid spam filter detection. In contrast, AI-based spam filters are trained to find more subtle differences between emails flagged as 'spam' and 'non-spam', and can improve their detection capabilities with new data feeds to keep up with spam generators. Thus a more useful definition characterises today's AI as:

"A system's ability to correctly interpret external data, to learn from such data, and to use those learnings to achieve specific goals and tasks through flexible adaptation."[2]

Figure 3. Artificial intelligence technology and innovation pipeline

Context

In 1951, the father of computer science and pioneering English codebreaker against the Nazis, Alan Turing, foresaw the potential for machines to out-think humans. Turing went so far as to devise a test of ML long before there were machines worth testing. The 'Turing Test' requires a person to ask a series of questions to both a computer and a human; if upon reading the responses of the human and machine, the questioner is unable to tell which is human and which is the computer, the computer would be described as exhibiting intelligent behaviour.[3] It would be more than half a century later for AI to truly come of age, enabled by mass digitisation to collect vast amounts of data, and an exponential increase in computer power required to process it.

Drivers

Innovation – The drivers of AI are simple: humans want to innovate. We want to do less, have more, and do better. And we want to know things. AI technologies have been driven primarily by tech people – computer scientists, engineers and the like – who want to push the boundaries and see how much machines can replicate human intelligence. Most scientists, corporations and governments want to do better at what they do: make profits; identify and treat illnesses; ensure security from terror or crime; reduce human error; use precious resources more efficiently, and so on and so forth.

Precision and personalisation – We all want to be treated as a unique person. Personalised health services are being used to understand the specific

"AI's capabilities and speed to carry out complex tasks are far superior to humans."
— World Economic Forum

care needs of patients better. AI systems are being developed to better respond to each person, including customised advertisements, criminal sentencing and parole decisions, identifying children at risk of neglect or abuse, and deciding if you are the 'best person for the job'.

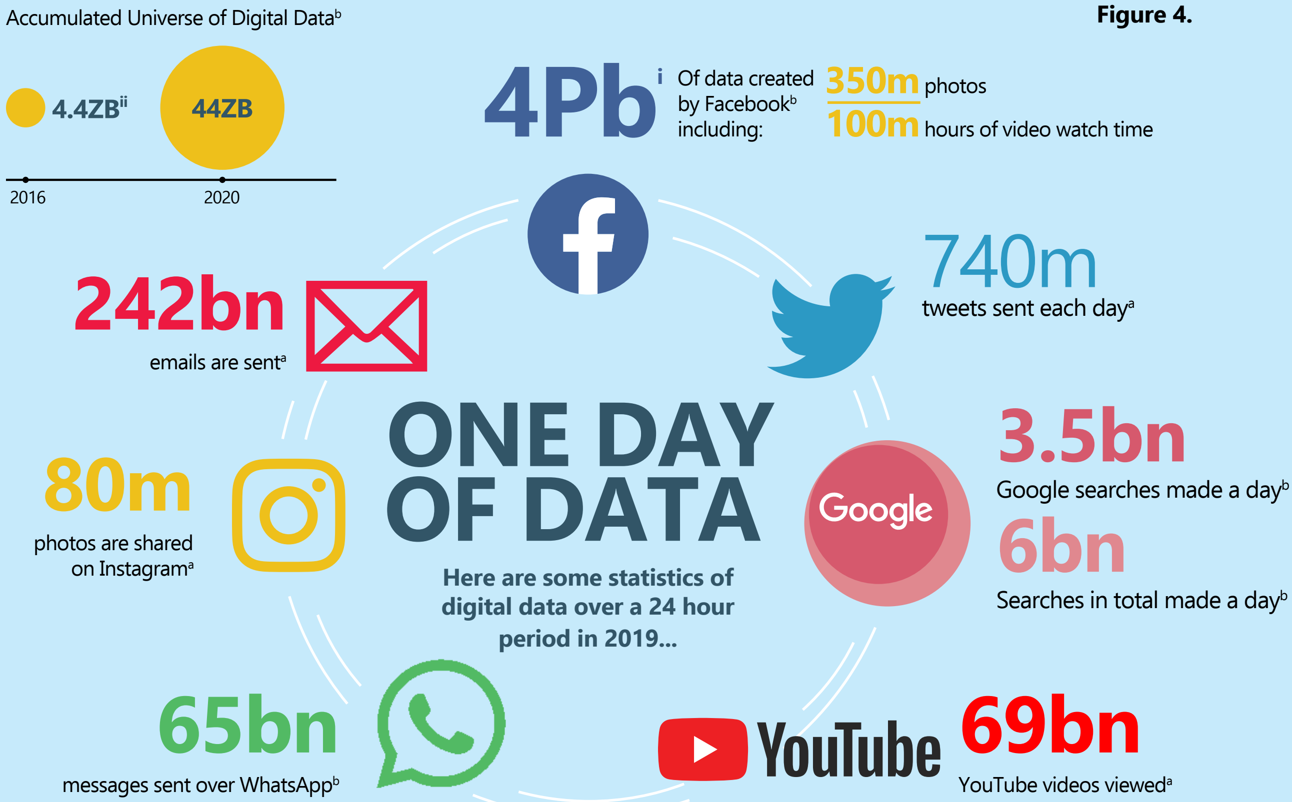
Efficiency and productivity – For industry, AI's appeal is in automation and robotic systems to reduce labour costs, improve efficiency and productivity, better utilise resources and standardise processes. Moreover, AI increases their ability to understand who their customers are and what they want, which in turn gives a competitive advantage. For end-users, AI's appeal lies in personalisation and convenience.

Enablers

Computing power and the ineffable 'cloud' – Advances in computers and electronics have closely followed Moore's law – a historical observation showing computing power and device complexity have doubled approximately every two years. Since AI relies on fast processing of large amounts of data, it has been enabled by exponential increases in computer processing speed and storage capacity, internet speed and 'cloud computing'.

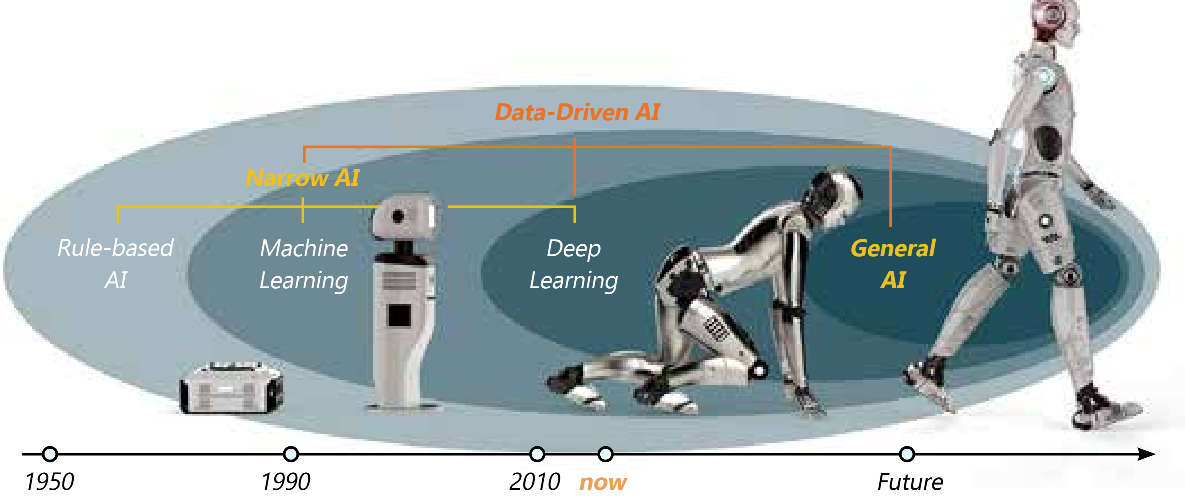
The Internet of Things – Technological innovations and economies of scale have seen dramatic price reductions in digital devices and, henceforth, higher usage. The so-called Internet of Things (IoT) are devices and sensors embedded into everyday household and mobile items connected directly or indirectly online. Smartphones, tablets, smart watches, televisions, remote sensors and equipment monitors, to name a few, capture real-time data that is fed into 'the cloud'. For example, Google Maps predict traffic conditions and travel times partly by using real-time GPS movements retrieved from its app users' smartphone to determine how fast they are moving.

Figure 4.



[i] 1 Petabye (PB) = 1 x 10^{12} Kilobytes (Kb) or 1000 terabytes. [ii] 1 Zetabyte (Zb) =1 x 10^{18} Kb or 1 million Pb. For comparison, the computers that put Apollo 11 on the moon contained just 4 Kb of processing power and 32 Kb of storage capacity.
Data sources: [a] www.internetlivestats.com (accessed June 2019); and [b] 'The Future of Data' Raconteur, 2019.

Figure 5. The evolution of processes that collectively make up 'artificial intelligence'



Next Generation Sequencing (NGS) – digital laboratory technologies have also revolutionised the generation of big datasets; perhaps none more so than NGS, which became a game changer in genomics in 2007. The Human Genome Project was the first of its kind to map the entire sequence of a human genome. Starting in 1990, it took 13 years to complete and involved some 20 global organisations at the cost of about US$3 billion.[4] With today's NGS technologies, an entire genome can be sequenced within a day or two for as little as US$1,000-2,000.[5] Affordable genome sequencing has created a global trend in online DNA ancestry companies that can trace the heritage of its customers, as well as unbeknown others. In the US, publicly available genomic data was used by FBI officials to track the 'Golden State killer'; creating debate around data privacy and consent.[6]

A key issue for regulators is ensuring that individuals are both aware of, and consent to, the collection of personal information by IoT devices. In general, users are aware of, and therefore, more likely to consent to the collection of information, which they have explicitly provided, such as when completing online forms. However, the industry in general has poorly educated the public about other forms of metadata being collected that can identify an individual. The European Union's General Data Protection Regulation (the GDPR), which took effect in May 2018 includes some regulations to address these issues (for instance, the 'right to be forgotten') that are currently not covered within the Australian Privacy Act.[7]

Inputs

Big Data – the enormity of data is what feeds modern AI. The enablers are things that produce loads of data: metadata, genomic, consumer behaviour, advertising and market response, economic and financial, spatial, environmental, weather, and the list goes on.

Once the data has been collected and digitally stored, key issues remain around **data ownership and protection of privacy**. By 2020, the amount of data in the digital universe will be 10-fold higher than just 10 years ago (**Figure 4**). Big data has become a highly valuable commodity. But who should own this data and who should have the right to access it? In light of recent cases such as the Cambridge Analytica scandal which used personal data from millions of Facebook users for targeted political advertising, several countries have adopted frameworks and legislation to keep up with the pacing problem in data collection, ownership and use.

Processes

From Narrow to General to Super AI – how we perceive what human intelligence is and therefore what counts as 'artificial' intelligence is evolving (**Figure 5**). Part of the ambiguity surrounding AI, is that its definition has changed in response to increasing computing abilities, challenging our notion of what counts as 'intelligence'. Computers are adept at calculations with enormous numbers in infinitesimal times (including the humble calculator), which we might have once considered as intelligent. Indeed, there are specific tasks such as calculation at which many systems exceed the capabilities of most humans yet accepting these computers as therefore being more intelligent than a human still seems disconcerting.

"Artificial intelligence can play chess, drive a car and provide medical diagnoses. Examples include Google DeepMind's AlphaGo, Tesla's self-driving vehicles, and IBM's Watson. This type of artificial intelligence is referred to as narrow (or weak) artificial intelligence – non-human systems that can perform a specific task. We encounter this type on a daily basis, and its use is growing rapidly".[8]

By contrast to narrow (or weak) AI, **general (or strong) AI** refers to a machine that can perform any task as well as, or better than a human and being able to adapt and respond to a wide variety of circumstances. This is the ultimate goal of many researchers in the field but is also the same type of intelligence which is most likely to realise human fears of rogue AI.

Machine learning uses data to 'train' itself – ML is a process for producing AI by enabling a computer program that can improve itself. Today, AI is often used interchangeably with ML, though it is in fact, a subset within AI. These systems can perform tasks without explicit instructions and update their algorithms in response to their own received inputs; much like a human, they can learn and improve with experience. ML's underlying algorithms use data to cluster patterns and make predictions based on inference. ML systems can be classified as supervised (e.g. 'trained') or unsupervised – often used for data mining **(Figure 6)**. For instance, imagine your boss asks you to segment your company's customer files into three drawers of your filing cabinet with each drawer containing 'similar' customers. Under supervision, your boss will go through some records with you and provide guidance on what features to categorise them by. Unsupervised, your boss will tell you to look at all the files and decide for yourself which features you think best distinguish different groups (here, you are data mining). The more files you look at, the better you will get at finding similarities and differences between customers.

Facial recognition is an example of **supervised ML**—it is trained with images of individuals' faces to define biometric features (e.g. the distance between your eyes and from forehead to chin), as well as 'facial landmarks' that create a unique 'facial signature' in the form of a mathematical formula. Facial recognition systems used by US law enforcement can identify a US citizen among 117 million people on its database.

Data mining is a form of unsupervised ML often used in business analytics to discover new insights about its markets and customers, and to make predictive analyses.[9]

Deep Learning is a more sophisticated form of ML – its power lies in its multi-layered structure, where each layer progressively extracts new information from lower levels. The multi-layered approach allows corresponding machines to not only follow pre-programmed decisions but to respond to changes within their environment. An example is autonomous cars that can make real time decisions about speed and direction by analysing sensor-based data without input from a human user.[10]

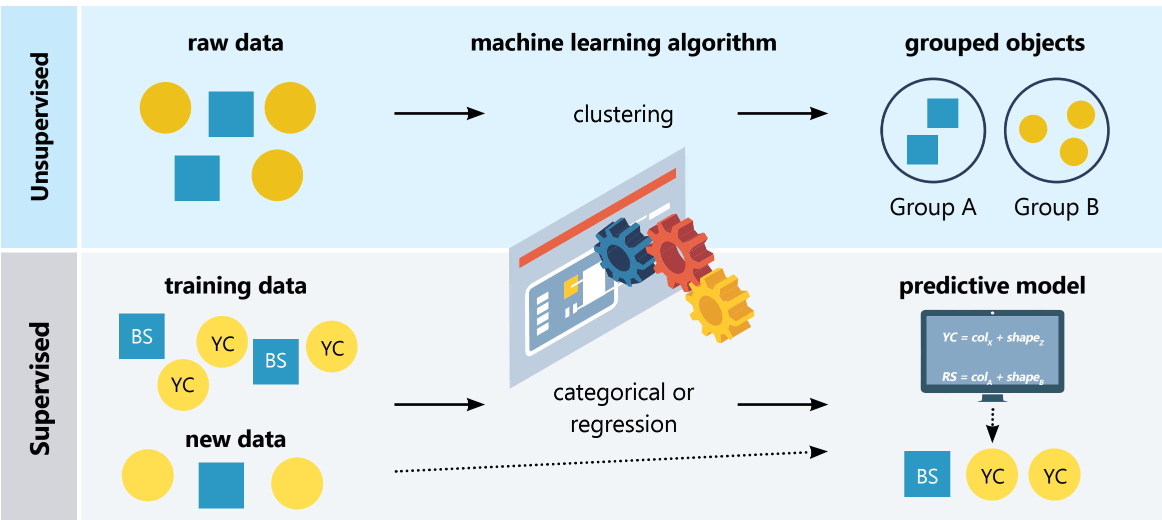


Figure 6. The processes of unsupervised and supervised machine learning

Will we all have our own version of *Iron Man's* J.A.R.V.I.S?

Artificial general intelligence (AGI) is the ultimate goal of some computer scientists. In *Marvel's* superhero world, Tony Stark's robot assistant J.A.R.V.I.S (Just A Rather Very Intelligent System) is perhaps the ultimate AGI system; able to understand and communicate in much the same way as a human can. J.A.R.V.I.S. has a range of functions – from running the Stark Industries business to managing the Stark Mansion and its security and navigating all of the Iron Man Armor – it is beyond general AI toward **artificial super intelligence** – exceeding the capacity of a human.

While AGI does not yet exist, AI systems are becoming smarter, faster, more fluid and human-like. British AI company DeepMind Technologies' AlphaZero program is making headway toward machines solving multiple-faceted problems with reinforced learning techniques – to such an extent that it taught itself to play Go, Chess, and Shogi without any pre-programmed knowledge of the rules and beat the world's best players. More recently, AI researchers developed an AI that can compete with humans in 3D multiplayer computer games.[11]

The inevitable rise of highly sophisticated quantum computing is expected to further revolutionise AI toward AGI in ways beyond imagination.[12]

The ethics of AI decision making underlying the algorithms that act on data add layers of complexity – Key issues centre around transparency, explainability, responsibility and fairness. While some processes are aimed to reduce human bias, likewise it must be ensured that these pre-existing biases are not simply transferred from humans to machine. The problems are intensified with 'black box' systems where there is a lack of transparency and knowledge of the algorithms underlying the decisions required. Moreover, caution must be taken to use proxies, where firm data is absent, to infer outcomes. Several recent cases in the US have highlighted AI algorithms causing discrimination, such as determining if children are at risk by using data such as welfare support granted to parents in their algorithms or using location-dependent crime statistics in judicial support tools to infer the likelihood of criminals re-offending, often discriminating against individuals from African American neighbourhoods.

A notable example is the COMPAS sentencing software used in the US to inform judges of the likelihood incarcerated persons will re-offend. An independent study found the software was biased against African Amercians who were unfairly categorised as a higher risk. When challenged, the software developer refused to release the AI-algorithm underlying the software, claiming protection of their intellectual property.

Outputs

The scope and potential applications of AI are enormous and are being incorporated into virtually every sector (**Table 1**) as more and more businesses and government agencies are finding uses for it. The main applications centre on predictive analytics, robotic automation, transportation, and decision making. Many agencies are adopting biometric systems to streamline identification in law enforcement, immigration, correctional services and investigations. Text analytics and natural language processing are being used for security systems and fraud detection. Digital twins create virtual replicas of physical objects (non-living and living) to monitor equipment and infrastructure – such as aircraft engines, gas turbines, and bridge structures – and predict failures with cloud-hosted software models of machines.

Unsurprisingly, the tech giants are dominating the market for the most on-trend consumer products too: Chatbots such as Amazon's Alexa home assistant, that has a remarkable ability to

Table 1. Applications of artificial intelligence by sector

Sector	Products and services
Health and aged care	• Remote patient monitoring enables longer independent living for the elderly and enhances health in remote areas • Genomics and biomarker discovery for detection of inheritable diseases • Image-based diagnostics lessen physician analyses of medical scans • Drug design data mining of proteomics can lead to better-targeted medicines • Autonomous robotic surgery • AI-driven technologies that enable participation by people with disabilities
Education and research	• Dubbed the "invention of a method of invention" – AI can be used to accelerate the pace of research and development from drug discovery and design to protein folding and advanced materials • Virtual teaching assistants • Learning analytics to develop individualised teaching and assessment materials tailored to current knowledge and learning performance
Energy, mining, manufacture	• Grid energy demand AI-systems to optimise energy distribution • Machine performance monitoring can increase efficiency
Human services	• Robotic process automation systems mimic user behaviour to learn how to do multiple, non-straight forward tasks, such as identifying emailed invoices, reading non-standard fields, entering into an accounting system and filing. • Speech recognition and Natural Language Generation transcribe human language and interact with humans for customer service, support and engagement, and human resources
Business, finance and information technology	• Decision management systems to optimise performance, minimise risk, streamline operations and increase profits • Precision marketing matches targeted customers with products • Fraud detection and money laundering can be monitored with ML detection of unusual transaction activities • Cyber security systems: AI-driven cyber defence machines can now uncover suspicious user activity and detect up to 85 per cent of all cyber attacks
Agriculture and fisheries	• Plant disease monitoring and tracking • Water use optimisation • Harvest time optimisation with visual robotics • Wild animal pest prevention • Grading process of agriculture products • Water health monitoring of aquaculture farms
Government, justice and defence	• Welfare, employment and fraud detection • Personalised services to those assessed as high risk • Infrastructure monitoring can reduce maintenance costs and increase equipment lifespan (e.g. bridge monitors, automatic street light adjustments based on people movement) • New AI-driven regulatory compliance solutions are emerging that can automate processes and deliver comprehensive risk coverage • Judicial process assessment and case management software • Autonomous weapons to respond to threats in real time • Identification of cyber attacks

detect speech from anywhere in the room; Google-owned Nest is a thermostat that adjusts the room temperature to your heating or cooling needs; Netflix and Stan pre-select the movies and TV shows you are mostly likely to enjoy; Tesla's vehicles feature a myriad of uber-cool predictive capabilities, self-driving features and other customised luxuries; and, of course, Apple's Siri helps you manage your day while you're on the go, and wearable devices such as FitBit and Garmen keep track of your health and fitness, unlock your car and can even improve your golf swing.

Convenience and luxury aside, arguably the three greatest societal benefits of AI applications are:

1) Improvements in productivity, particularly in labour-intensive tasks, thus offering significant benefits to economic growth and development;
2) Improvements in road safety, with reports suggesting driverless vehicless can prevent up to 90 per cent of traffic fatalities; and
3) Improvements in health, wellbeing and life expectancy from the delivery of personalised medicines, early disease diagnosis, remote health services, patient monitoring and AI-driven technologies that can enable greater participation of people with disabilities.

Of course, many AI-driven applications may come with specific challenges and therefore require regulators to step in from various cross-sectors. Many of these challenges must be guided by ethics frameworks with key principles outlined in the CSIRO and Data61 discussion paper,[13] which underlines that AI applications must 'do no harm' and generate net-benefits (e.g. the benefits outweigh costs). Thus, while there is intense (and indeed justified) debate surrounding autonomous vehicles and the prioritisation of lives in the event of an accident, this must be considered in the overall context of the lives that will be saved. However, there are real safety risks, both existential and individual, posed by autonomous weapons in a way not seen since the advent of nuclear weapons. The convergence, splitting and globalisation of the digital nature of AI, will necessitate intense collaboration across multiple regulators, different levels of government, and between nations.

From an economic perspective, Data61 analysis reveals that over the past few years, 14 countries and international organisations have announced AU$86 billion for AI programs.[13] As with all disrupting technologies, the shifting nature of work will produce winners and losers. New markets and products will bring with them jobs and increased projects, as will large increases in efficiency and productivity through automation and reduced human error. Early adopting companies will gain a competitive advantage by better understanding their customers' needs and being able to respond with personalised products, services and prices. Here, governments must be mindful to support the small business culture underpinning the Australian economy to help them transition and benefit, and avoid a monopolisation by a handful of corporate giants.

Critically, estimates suggest that around half of activities performed in jobs, and between 21 per cent and 38 per cent of jobs in the developed world, may be lost as a result of an increasingly digitalised and automated economy.[14] However, a recent study conducted in the United Kingdom estimates that countervailing displacement and income effects are likely to balance each other out over the next 20 years or so. Thus, as AI displaces traditional jobs to automation, reskilling and transition planning are required to create the jobs of tomorrow.

For the environment, AI-driven systems can create a number of positive impacts and help to tackle the most critical challenges such as climate change and pollution. Monitoring systems and feedbacks will improve energy efficiency and reduce emissions (e.g. equipment sensing with smart cooling/heating), minimise resource waste and pollution (e.g. smart watering and fertiliser for crops), predict and manage natural disasters, and can also be used to evaluate the impact of ecosystems services, which can in turn be used by environmental decision makers to understand and quantify environmental assets.[15] AI-based modelling can assist in planning resource management decisions, and help manage disaster responses to natural catastrophes, such as predicting bush fire movement.

The perceived lack of regulation surrounding AI has seen it deemed as the new 'wild west'. The past few years have seen several government and research organisations throughout the world develop policy and regulatory responses, or ethical and regulatory frameworks to manage AI ethics and ensure the risks do not out way the benefits. These include the UK, EU, Germany, France, Canada, US, Singapore, Japan, India, and China.

Fortunately, Australia has policies and regulations in place that can be used and enhanced to include AI. These include privacy and data protection laws, as well as possibilities for legal redress for faulty products and harms caused by products or erroneous organisational decisions.

Some authors propose that the use of AI in decision-making should come with a label (a 'Turing

Stamp'), similar to food labelling. Alternatively, some jurisdictions require AI decision-making in government to pass an examination for fitness for purpose and ethical compliance. Rights-based frameworks building on recognised human rights and digital rights (of data protection and privacy) have also been offered. A discussion paper led by CSIRO and Data61 and funded by the Australian Government Department of Industry, Innovation and Science outlines an ethics framework for Australia. Within it, they offer core principles for AI and propose a toolkit for policy makers and regulators – it is a valuable resource which is well worth reading.[13]

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Sorting out the 'good' from the 'bad'

The Ethics of High-Tech Tools Making Decisions

AI is often sought to help classify individuals in sub-groups to identify the most appropriate responses to each person. For example, deciding what level of airline passenger screening a person must undergo, or the Chinese government's social credit system, can open up opportunities for 'good' citizens while blocking those categorised as 'bad'. Similarly, AI can generate predictions of an individual's circumstances by comparing their characteristics to a dataset of others. For example, they could identify the level of risk a child faces in suffering abuse or neglect.

Such processes of classification and prediction are very helpful for governments in better tailoring responses to people, instead of a 'one-size-fits-all' approach. They also enable resources to be better targeted and used more efficiently and effectively.

There are a wide range of areas in which AI is being used or on the verge of being used to assist government make decisions. Apart from those already mentioned, judicial processes in the US are making use of AI to help inform judges about the appropriate sentence for an offender, such as time in prison, non-custodial sentences or alternative correctional responses. They are also being used to help inform parole officers about the likelihood of reoffending when on parole, to help parole officers decide if a person should be released on parole. In security systems, AI based facial recognition is not just used to find a match for a 'person of interest' or to serve a warrant. AI enhanced CCTV systems have also been trialled for the London Tube system to identify people who may be about to suicide by jumping in front of a train by following their movements on the platform and comparing that with previous movement patterns of previous suicide attempts.

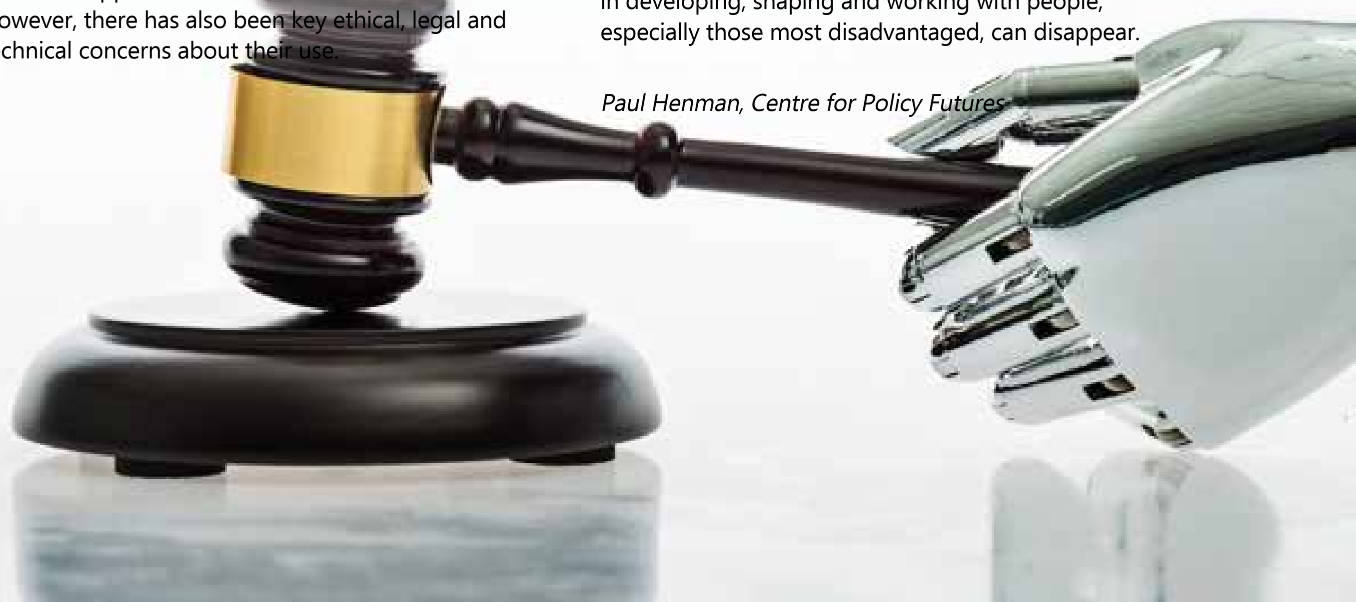
On face value, all of these current and emerging uses of AI appear to be of considerable value. However, there has also been key ethical, legal and technical concerns about their use.

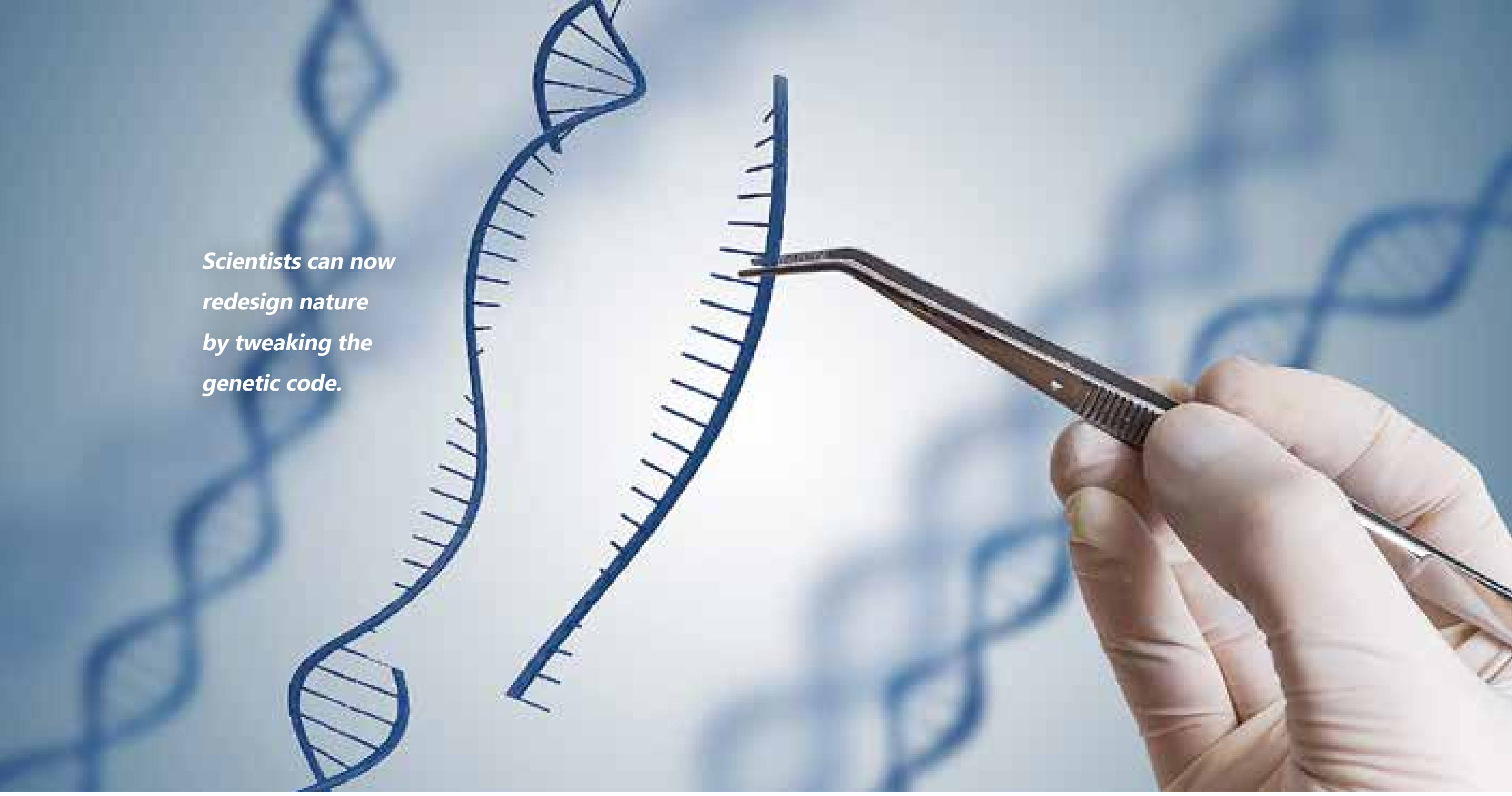
Data bias is at the heart of much criticism of the uses of AI in juridical sentencing and parole decisions, and similarly with child abuse and neglect detection. In the former, the data is based on a historical racial bias and so the AI, if not developed carefully, will continue to reflect, reproduce and even exacerbate such bias. In child protection, the bias is about poverty and disadvantage, whereas just being poor and using public (rather than private) services can misleadingly label a child as at risk of abuse or neglect. Indeed, when Amazon used AI for hiring decisions it found such a strong gender bias that the company ceased its use. The lack of transparency of the AIs in use is also a repeated concern. It is quite common for AIs to be developed by commercial companies and used in a modified 'off the shelf' basis, with limited configuration to the specificities of the use location. As commercial products, the assumptions and data used to develop the AI remains inaccessible behind 'commercial in confidence' protections.

The black boxed nature of these systems also means that government employees and people affected by AI decisions have limited ability to understand and question the AI decisions, thereby undermining public accountability and review processes. In relation to predictive AI whereby a system suggests something about a person in the future, it is often not realised that prediction is not the same as actuality. How we treat someone based on what may occur, rather than what has occurred, needs careful consideration. Otherwise we end up defining futures for people that they have little or no control over.

Workforce considerations also occur with the growing use of AI in government decision making. If an unskilled officer can use an AI, or it can operate autonomously and independently without human involvement, skilled professionals could be lost and with that the important role of human factors in developing, shaping and working with people, especially those most disadvantaged, can disappear.

Paul Henman, Centre for Policy Futures





"Writing Biological Code: A biological cell is very much like a computer — the genome is the software that encodes the instructions of the cell and the cellular machinery is the hardware that interprets and runs the genome software. Major advances in DNA technologies have made it possible for biologists to now behave as software engineers and rewrite entire genomes to program new biological operating systems." J. Craig Venter Institute

Synthetic Biology

Definition

Modern engineers design, build, and test complex machines and structures from a range of parts and materials with known or predicted functions. Synthetic biology extends these engineering principles to living systems to design and construct improved biological organisms and pathways with a range of goals from improved agricultural productivity, to pest and pathogen control, and ecosystem protection and conservation.

A core principle of synthetic biology is to simplify, optimise and streamline desired processes and pathways by removing genetic redundancy.[1] To achieve this, synthetic biology aims to understand how biological systems work; break systems down into their simplest functional 'parts'; categorise and catalogue their DNA blueprint into libraries; and draw upon this repository of standardised DNA parts to design, build and test new systems. The desired result is to produce highly biological machines, components, circuits, systems and, indeed, even entire organisms that do not exist in nature.

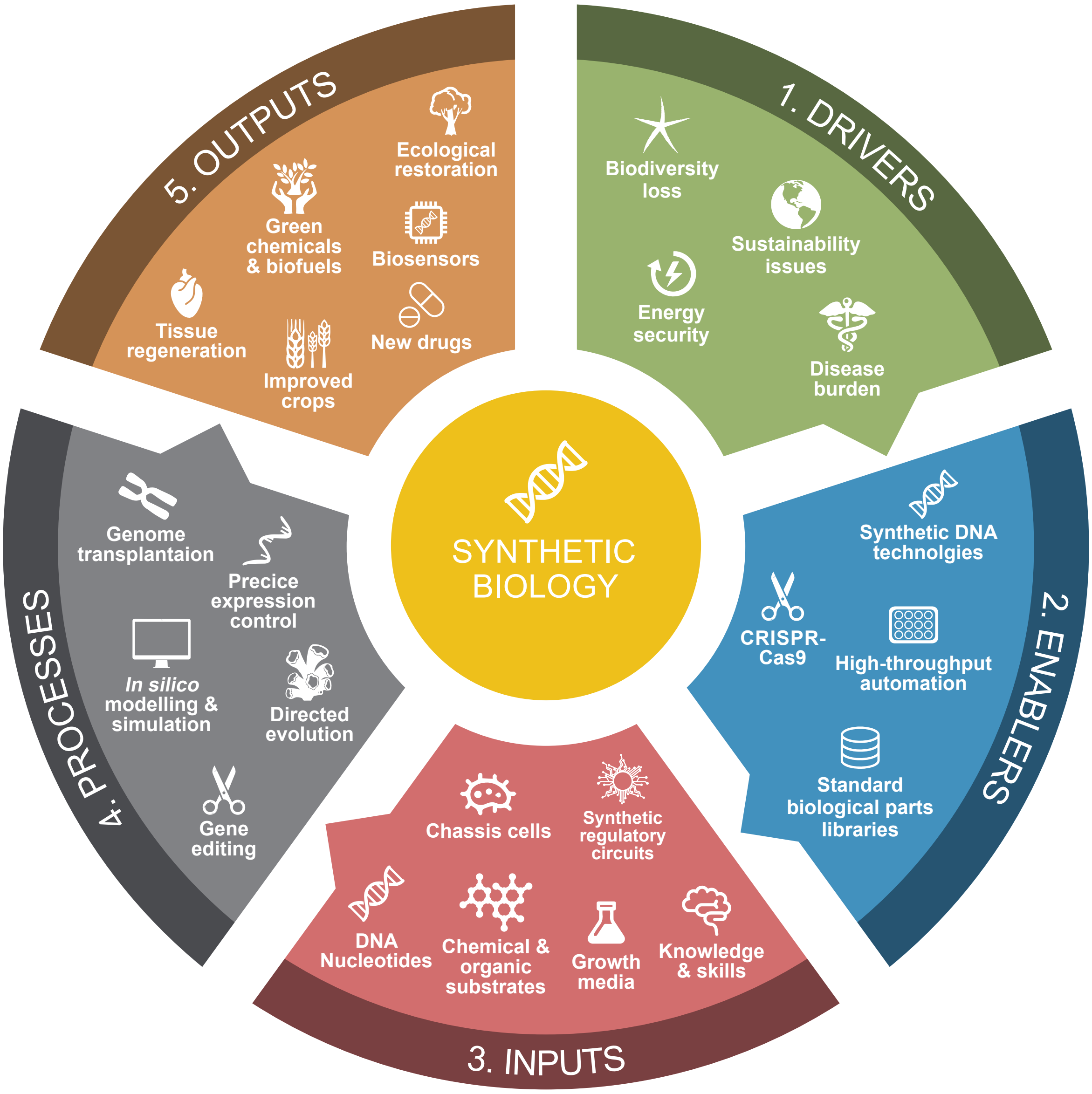
Synthetic biology converges several disciplines – molecular biology, systems biology, bioengineering, information technology, artificial intelligence, analytical chemistry, and classical engineering.

How does synthetic biology differ from genetic engineering?

Synthetic biology emerged from genetic engineering and uses many of the same tools involved in recombinant DNA. While genetic engineering relied on transferring naturally occurring genes from one organism to another, synthetic biology's suite of tools and knowledge enable higher precision, predictability, sophistication and optimisation. This systematic, less *ad hoc* approach improves the rate of novel discoveries and bring products to market much more quickly.[2]

For example, to confer disease resistance in a food crop, a traditional genetic engineering approach might involve screening for organisms with natural resistance to a disease, determining a gene or genes involved and the respective DNA sequence, extracting the DNA from the host and transforming

Figure 7. Synthetic biology technology and innovation pipeline



it into a random location of a food crop's genome. In contrast, a synthetic biology approach might use computational modelling supported by functional genomics data, to design, build and test novel genetic elements that produce a highly efficient immune response in the host.[3] These interations of design-build-test coupled with automated robotic assembly and high-throughput tools give researchers a much larger 'solution space' for improvement options than could otherwise be achieved working at a lab bench.

Context

For at least 30,000 years, humans have been manipulating the genetics of plants and animals to accentuate desirable traits.[4] This deliberate selection for traits is the fundamental difference between agriculture and earlier forms of horticultural production. Food crops such as corn have been selectively bred to improve taste, appearance and nutritional content to such an extent that domestic varieties are today completely

"Synthetic biology aims to design and create full genetic systems that can be implemented in an organism in order to perform a self-regulated task. This does not imply just recombining DNA, but designing and modeling a novel pathway by assembling many different pieces of genetic material collected and characterised from natural organisms." (Rey, 2017)[13] unrecognisable from their wild antecedents (teosinte). A range of animal species have been domesticated by selection for sociability and other useful traits to a similar point – consider the differences between a wild wolf and a pet dog.

The birth of modern genetics with the discovery of DNA as the molecular basis for inherited traits catalysed a succession of rapid advances from the 1950s onwards. Notably, the first genetically modified organism (GMO) was developed in 1973 by Herbert Boyer and Stanley Cohen by transferring an antibiotic resistance gene from one bacterium to another.[5]

Global commercialisation of GMOs occurred after 1982, following a landmark ruling by the US Supreme Court that granted permission to General Electric to patent a GMO bacteria they developed to break down crude oil in the event of environmental spill.[4] This led to a wave of venture funding and start-ups for GMO applications in food and medicine. A prominent milestone of industrial biotechnology was the production of human insulin expressed in a genetically modified bacterial cell line – the first pharmaceutical approved by the US Food and Drug Administration (FDA).

Since then, the exponential growth and digitalisation of knowledge in genomics, genetics, metabolic pathways and protein functions – fuelled by research, investment, computing power and other technologies – has led the emergence of ever more sophisticated synthetic biology, what some have dubbed 'genetic engineering 2.0'.

The power and possibility of synthetic biology was realised in 2010 when researchers at the Venter Institute announced the world's first entirely synthetic life form – a single-celled organism based on an existing bacterium that causes mastitis in goats, but at its core is an entirely synthetic genome that was constructed from three chemicals in the laboratory.[6]

Just as technological developments have come thick and fast, private and public investment in synthetic biology companies has grown at a remarkable rate too. According to the US-based synthetic biology advocacy organisation SynbioBeta, investment in US-based synthetic biology firms has risen from ~US$200 million in 2009 to US$1.8 billion in 2017 to approximately US$3 billion in 2018. Governments have also invested in the field and several countries including the US, UK, EU, Finland, the Netherlands and China, have now outlined roadmaps to integrate its technologies into their economy.[1]

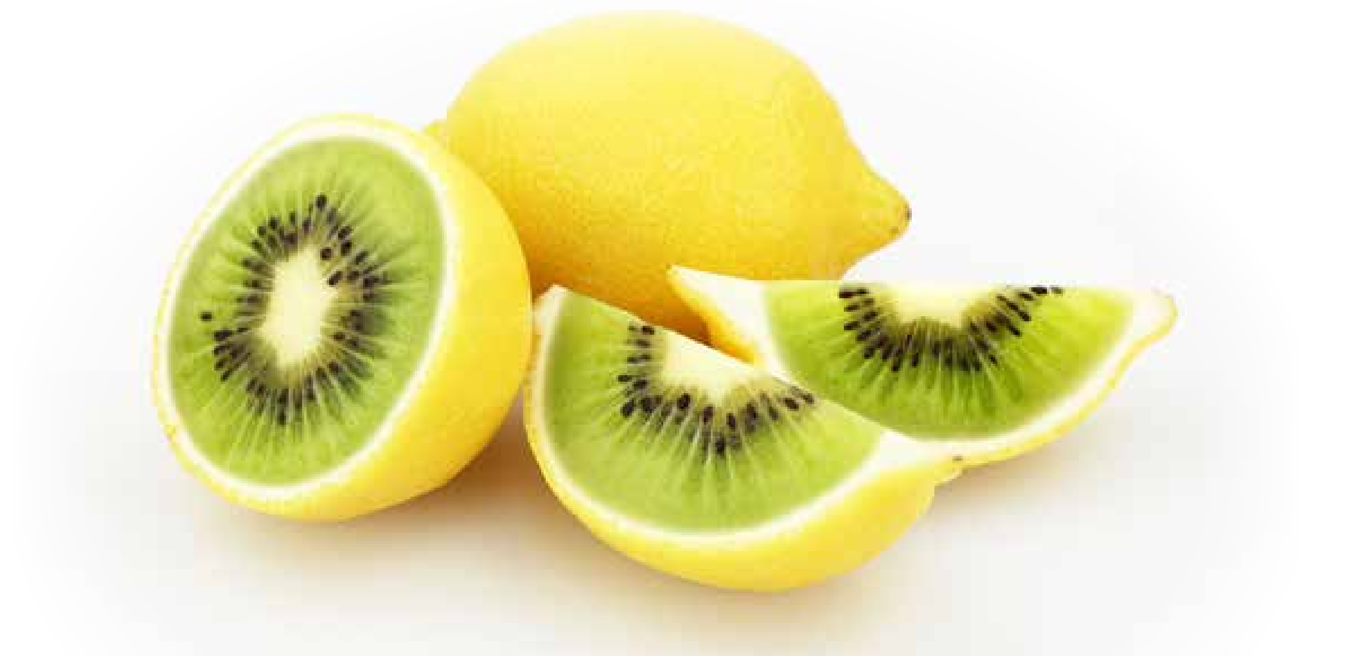
The technology's potential is also being realised in the rapid growth of its market value – in 2015, the synthetic biology components market was valued at $US5.5 billion and is anticipated to reach US$40 billion by 2020. These figures are just for 'DNA parts' and do not include revenue from synthetic biology products which are also expected to follow this trend. In 2016, bio-based chemicals constituted only two per cent of the US$1.2 trillion dollar chemicals market yet advances in synthetic microbial factors anticipate this share will rise to 22 per cent by 2025.[7]

Drivers

Synthetic biology may offer promising solutions to some of the most complex challenges of today, including:

Replacement of petrochemicals with sustainable chemicals and fibres – a transition to a bioeconomy seeks to reduce reliance on fossil resources. Hence, Bio-based production of fibres and chemicals from sustainable and renewable feedstocks have been a key driver in synthetic biology, with many commercial projects to date.

Sustainable intensification of agriculture – new and novel methods of food production are critically



needed to meet increasing food demand which is projected to increase by 25 to 100 per cent to sustain a population of nearly 10 billion people in 2050. In parallel, agricultural-related greenhouse gas emissions, nutrient pollution, and water usage must be significantly reduced to operate within safe planetary boundaries.

Energy security and climate change – likewise, the development of renewable, CO_2-neutral high-quality biofuels that don't require the use of foodcrops (such as corn-based bioethanol) may be required to meet an increase of 27-60 per cent in energy demand from 2010 to 2050. For example, despite growth in wind, solar PV, hydro and battery technologies in support of electricity demand, liquid fuels may be required in heavy transport such as aviation and shipping.

Disease burden and the high cost of new drug development – the rise in 'affluent' chronic non-communicable diseases (including Alzheimers, cardiovascular disorders, cancer and diabetes) in developed nations and the ever present risk of disease epidemics in developing nations continues to drive the need for new drug development.[2] Yet despite the trillions of cumulative dollars invested over the past 70 years, new drug development has been impeded by long timeframes (average 10 years), high costs (US$1.8-$3 billion) and poor success rates (as low as 0.01 per cent).[8]

Environmental restoration, adaptation and biocontrol – increases in air, water and soil pollutants and habitat destruction are wreaking havoc on earth systems, posing a threat to society, biodiversity and indeed entire ecosystems such as coral reefs. This is driving the development for new and scalable bioremediation and biomonitoring solutions to restore and protect environmental systems.[2]

Enablers

A collaboration led by Massachusetts Institute of Technology (MIT) researchers to create the **BioBricks™ standard of interchangable DNA parts** and make available via the open source **Registry of Standardised Biological Parts** (iGem Foundation) enables rapid prototyping of new biological systems by combining established components that are easily assembled.[10]

DNA Synthesis technologies – nowadays, an increasing number of companies provide commercial DNA synthesis which has seen a drastic reduction in cost and time to deliver novel DNA constructs.[9] *De novo* synthesis techniques that remove the need of a pre-existing template (e.g. polymerase chain assembly (PCA)) have provided a breakthrough in allowing the creation of larger synthetic DNA constructs.

Next generation sequencing technologies – see Artificial Intelligence sector.

High-throughput automation – including automated liquid handling machines and other robots that miniaturise biological reactions and provide high-throughput capabilities.

CRISPR-Cas9 Gene Editing technologies have enabled greater precision and control to modify existing gene sequences *de novo*, including inserting new genes, tweaking existing genes to perform better, or interrupting gene function, contrasting traditional genetic modifications that had much uncertainty of knowing where the foreign DNA would be inserted and what other side effects it may produce.

Bioinfomatics and computational biology – the field of bioinformatics has emerged as a computational process pipeline to make sense out of large data sets produced from DNA sequencing. Mathematical algorithms, statistical techniques and software tools combine to assemble the fragments into a digital recreation of chromosomes and entire genomes and to interpret, annotate and visualise the data. This digitalisation and its accessibility has been pivotal in allowing researchers to understand the blueprints of an organism and to visualise it in order to study the structure and functional relationships. Recently developed and highly sophisticated *in silico* modelling techniques now enable predictive outcomes of tweaking and designing biological components to accelerate the creation and testing of new biologics.

Inputs

In essence, the fundamental resources needed for any synthetic biology application are the data to model and design biological components, systems and organisms, and the DNA nucleotides to synthesise the designed DNA construct. Of course, depending on the application and process, you may also need a host cell to contain the system, or at least enzymes and substrates in the case of cell-free systems. Other consumables to grow living systems are growth media and the essential amino acids to build the expressed proteins, and, if synthesising products, the substrates the system will act upon to produce the desired end product.

Non-physical inputs are the enormous repository of biodata including genomic data and its associated translated proteins and their functions, which underpin the computational-aided modelling of metabolic pathways, circuits, and improvements in protein function.[11] Critically, **skills** are a key requirement and will require a conceptual change in the way that science is done. Researchers and educators must work to develop new training methods and courses to prepare researchers and research managers.

Processes

Rational Engineering: Design-Build-Test-Learn[12] – the simulation and testing of biological designs using computer software is an emerging opportunity to evaluate biological interactions across organisms, and potentially even ecosystems, prior to the release of a modified organism, but there remain challenges in accurate modelling of complex systems.

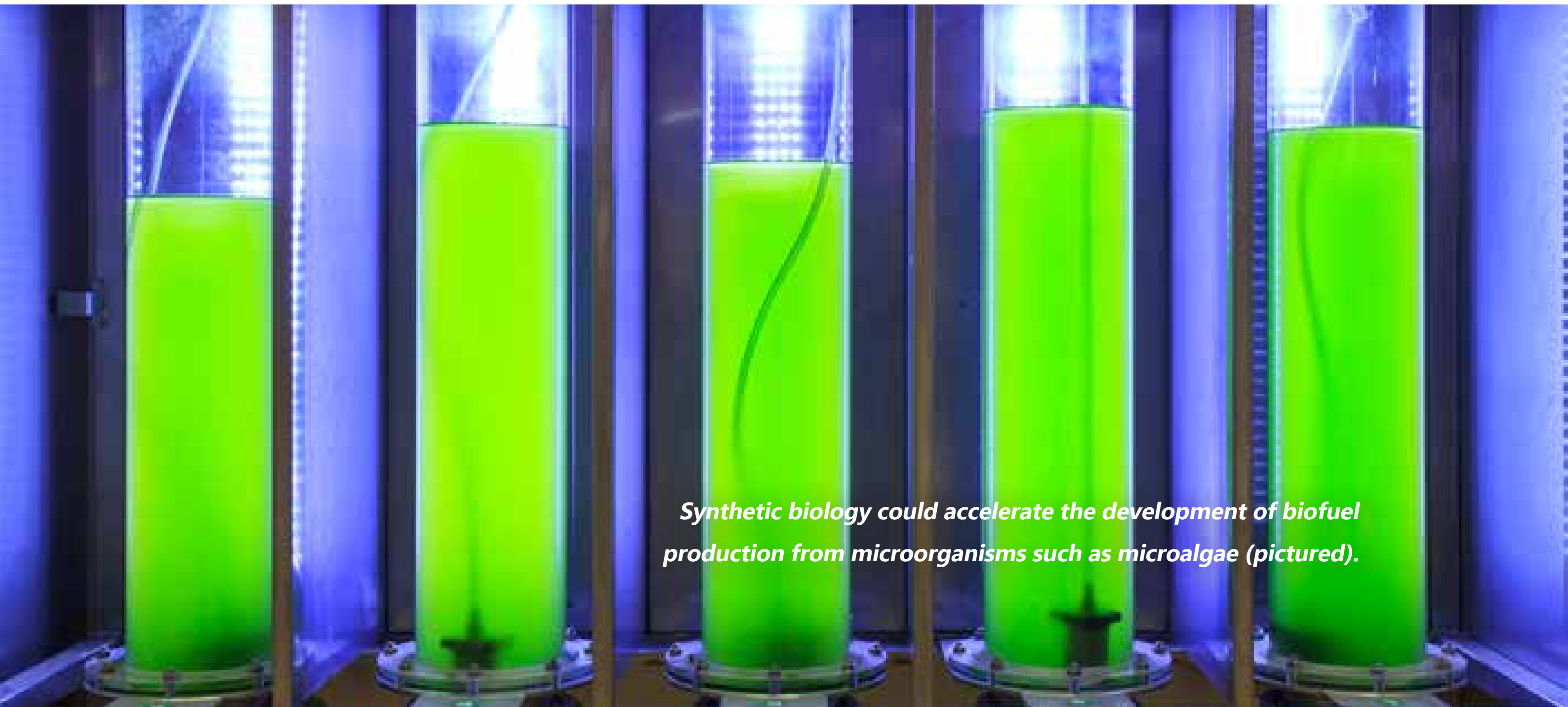
While there are several types of processes to achieve synthetic biology outputs, a typical systematic approach for simulation and testing of biological designs, particularly for microbial cell production (e.g. fine and specialty chemicals and fuels) is the **Design-Build-Test-Learn** pipeline shown in **Figure 8**.[14]

The **design stage** uses BioBrick libraries and computation modelling to select DNA parts and enzymes and optimise the DNA sequence to enhance performance. The **build stage** uses Artificial Gene Synthesis (also known as DNA Printing) to produce and assemble parts into functional DNA elements. These are inserted into a host cell or expressed *in vitro* using cell-free techniques. A popular synthetic cell—the **chassis cell**, so called for its likeness to the skeleton base of a car—provides a 'bare bones' genome with minimal functions so that more energy can be directed into producing end products. The **test stage** encompasses high-throughput methods for the growth of microbial production cultures, automated product extraction, and screening assays. Results are analysed at the **learn stage** through predictive models using statistical methods and machine learning to inform the next round of design. If required, a number of iterations of the Design-Build-Test-Learn cycle are completed until successful prototypes are identified, whereafter, they can be developed for scale-up.

Outputs

There are a growing number of commercial and social applications for synthetic biology. For instance, designed DNA constructs assembled into bacteria are creating highly efficient 'cell factories' that can produce chemicals as well as novel therapeutic proteins and peptides, and cell therapies.

Regenerative medicine, cancer therapies, and disease control – Synthetic biology is being used to create novel vaccines and antibiotics. Even more significantly, a successful lab demonstration recently showed a CRISPR-based gene drive of malaria-resistance genes into mosquitoes with inheritance in successive generations, potentially offering a route to malaria eradication.[15] In terms of drug production, the antimalarial treatment 'artimisinin' can now be produced by yeast, avoiding the need to isolate it from Chinese sweet wormwood plant. This helps to stabilise global prices.[16] The prospects for engineered immune-cell-based cancer therapies are also being improved by synthetic biology by enabling



Synthetic biology could accelerate the development of biofuel production from microorganisms such as microalgae (pictured).

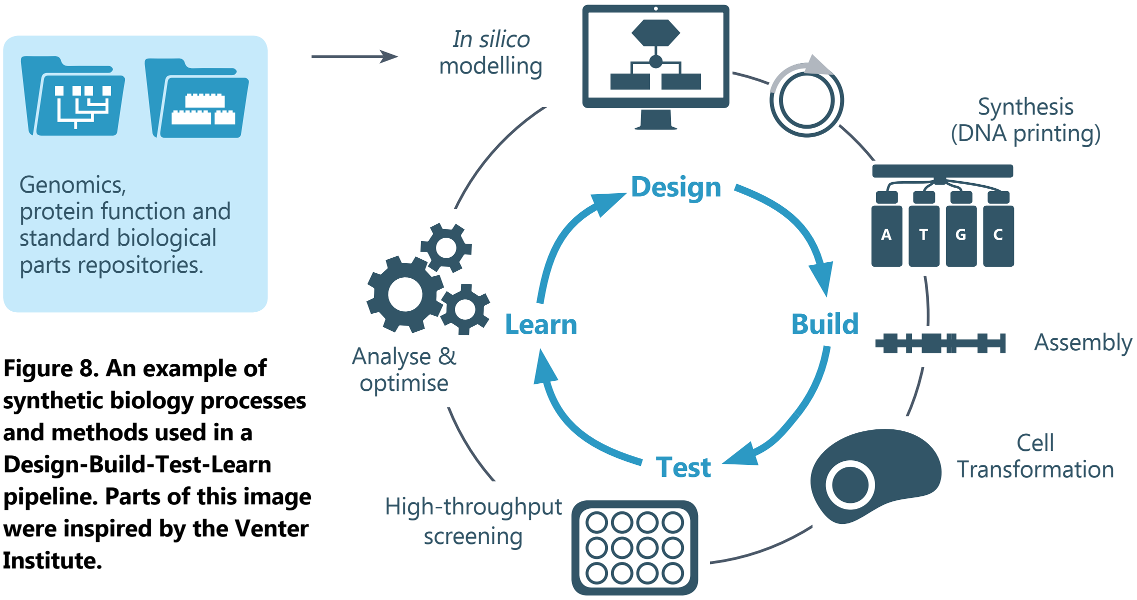


Figure 8. An example of synthetic biology processes and methods used in a Design-Build-Test-Learn pipeline. Parts of this image were inspired by the Venter Institute.

more precise targeting of cancer cells without damaging healthy cells.[17]

Similarly, regenerative research improving regenerative tissues *in vitro* restore normal function, by manipulating the genetic pathways that lead to self-organisation of multicellular systems.[18]

Bio-industrial production of fuels and 'green' chemicals – industrial scale production of sustainable alternatives to petrochemicals is being developed in yeasts and microbes by optimising conversion pathways of substrates into stored biochemicals. A more promising environmental prospect is via microbial photosynthetic conversion of atmospheric CO_2 into feedstocks for biofuels, using microalgae and cyanobacteria.[19] More commercially-viable ventures are emerging for bio-based 'green chemicals'. For instance biotech and chemical companies Genomatica and BASF collaborated to engineer a synthetic biology production route for the chemical butanediol that was viably commercial in just five years. Butanediol is used to produce an estimated 2.5 million tonnes of plastics and other polymers each year, including half a million tonnes of Spandex (Lycra). In 2011 all of this molecule came from petrochemicals. In 2025, however, it is estimated that 22 percent of chemicals will be synthesised biologically, reducing the need for harmful chemical pre-cursors.

Gene drives and directed evolution – are being investigated for use in agriculture and conservation efforts to confer resistance genes into populations using precise editing or endogenous genes or insertion of designed genes (see **Case Study**).

Biosensors – are being developed to provide more targeted and sensitive bio-monitoring applications. For example, in the environment they are used to monitor heavy metals in waterways and soils, while in the body they are being used to detect changes in metabolites (e.g. sugars in the bloodstream) or metastatic cancer cells.[20]

The benefits of synthetic biology to improve efficiency, cleaner and safer production methods, new and potentially better foods and healthcare options, and conservation of species warrant the further development of this technology for society, the economy and the environment.

But, if past experience of genetically modified organisms is anything to go by, public acceptance of synthetic biology processes and applications will be a key challenge to its wide-scale adoption. Here, governments can facilitate an on-going open dialogue to build trust and ensure the community is well informed of the risks and benefits. Australian regulation is keeping pace with new technologies: while much of the existing gene technology regulatory frameworks and regulations

"Australia will need to adopt international best practice in Responsible Research and Innovation (RRI) and ensure that ethical, legal and social considerations are integrated into this research and innovation process from its earliest stages. Scientists, regulators and policy makers must ensure that regulatory policies and processes have incorporated the legitimate concerns of the community."[1]

for recombinant DNA technologies still apply for synthetic biology, amendments have been recently made to the *Gene Technology Act 2000* and *Gene Technology Regulations 2001* to reflect new synthetic and genetic processes and applications.

Moreover, governments can mitigate the ecological and health risks raised by synthetic organisms by supporting rigorous research and testing of synthetic organisms and products prior to their release. In particular, regulators must be aware of the specific needs of different communities within Australia and internationally. For instance, Kowal (2015) noted that "there is much work to be done to address the ethical concerns that Indigenous people have raised, particularly unresolved and emerging issues such as collective ownership of samples, repatriation, and the use of Indigenous biospecimens that exist beyond national borders."[21]

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Recommended Further Reading

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Designing climate resilience into coral reefs

The Great Barrier Reef (GBR) is the world's largest living organism, supporting nearly 9,000 species of marine life over 2,500 individual reefs. In 2016-2017, extreme heatwaves created a back-to-back bleaching event, destroying a third of all GBR corals and causing widespread loss of biodiversity.[21] In parallel, pollution runoff, outbreaks of crown-of-thorns starfish, severe weather events and ocean acidification have exacerbated the decline of reef health.[21]

Despite international obligations of climate action set out in the 2016 Paris Agreement, latest reports by the International Panel on Climate Change predict a 95 per cent likelihood that temperatures will exceed a 2 °C rise by 2050, and could well be as high as 3 °C. Thus, some researchers argue that novel technological interventions are needed in parallel with conventional management tools to thwart further decline. Strategies that have been put forward include: engineering artificial reef structures, selective and assisted breeding, genetic engineering, reef cooling and synthetic biology.

What is coral bleaching? Corals have a mutually beneficial relationship with tiny algae cells that reside in their tissues (*Symbiodinium* sp.). — the coral supplies nutrients to the algae which, in turn, photosynthesise to provide the coral with energy, amino acids and oxygen. Upon changes in temperature, the algae produce high amounts of free radicals that cause oxidative stress to corals, triggering a cascade of events that eventually expels the algae from their tissues, producing the white 'bleached' appearance.[22]

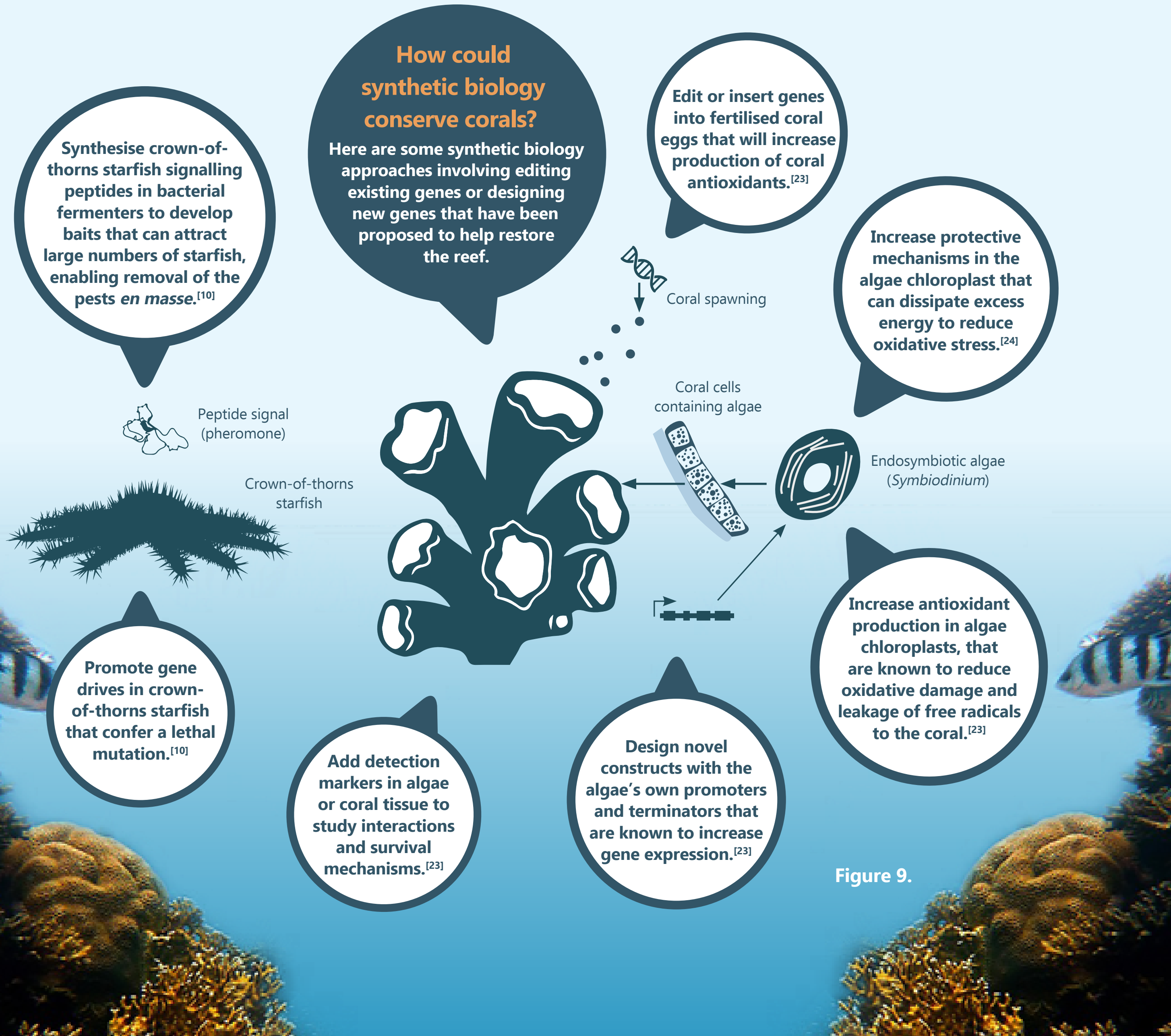
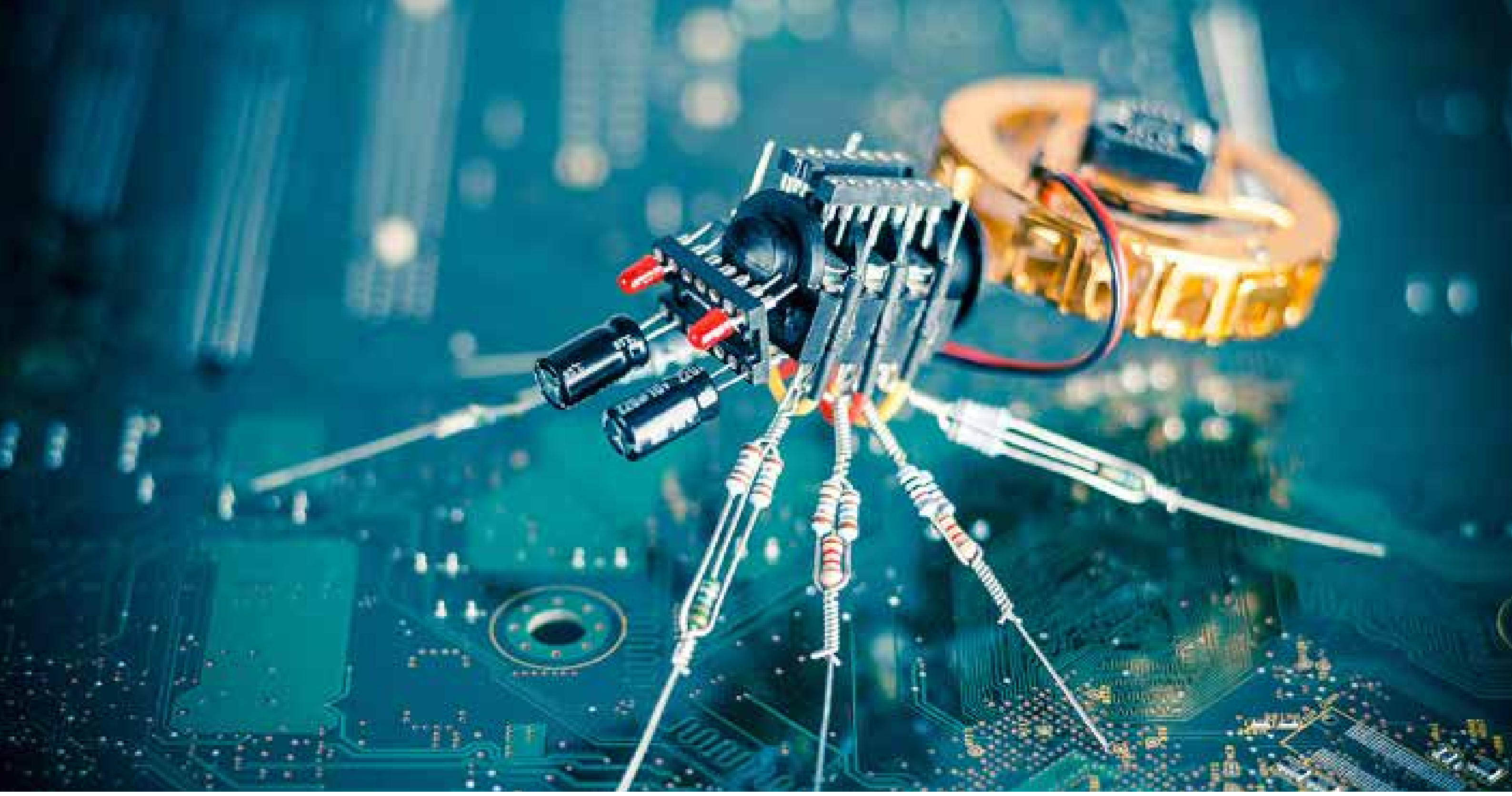


Figure 9.



"I can hardly doubt that when we have some control of the arrangement of things on a small scale we will get an enormously greater range of possible properties that substances can have, and of different things that we can do."
Richard P. Feynman, American Nobel Physicist, 1959.

Nanotechnology

Definition

Nanotechnology can be straightforwardly defined as the manipulation and manufacture of materials and devices at the 'nanoscale'; which is typically considered to be at dimensions between 1 and 100 nanometers. To put that in perspective, imagine 1 mm on a ruler, now cut that into a million pieces; or comparatively speaking, if the diameter of a marble was one nanometer, then the diameter of the Earth would be about one metre.[1]

Of course, nanotechnology is not a uniquely human invention. Nature has been exploiting processes at nano-scales (i.e. nanotechnologies) for billions of years – the process of photosynthesis, the creation and repair of cells, and the replication of DNA all rely on an organism's capacity to organise different kinds of atoms and molecules into complex microscopic structures. These sorts of nanoscale processes underlie the fundamental biochemistry of life. Nor are nanoscale materials new – nanotechnology has been used in sunscreens for many years in the form of titanium dioxide and zinc oxide nanoparticles.

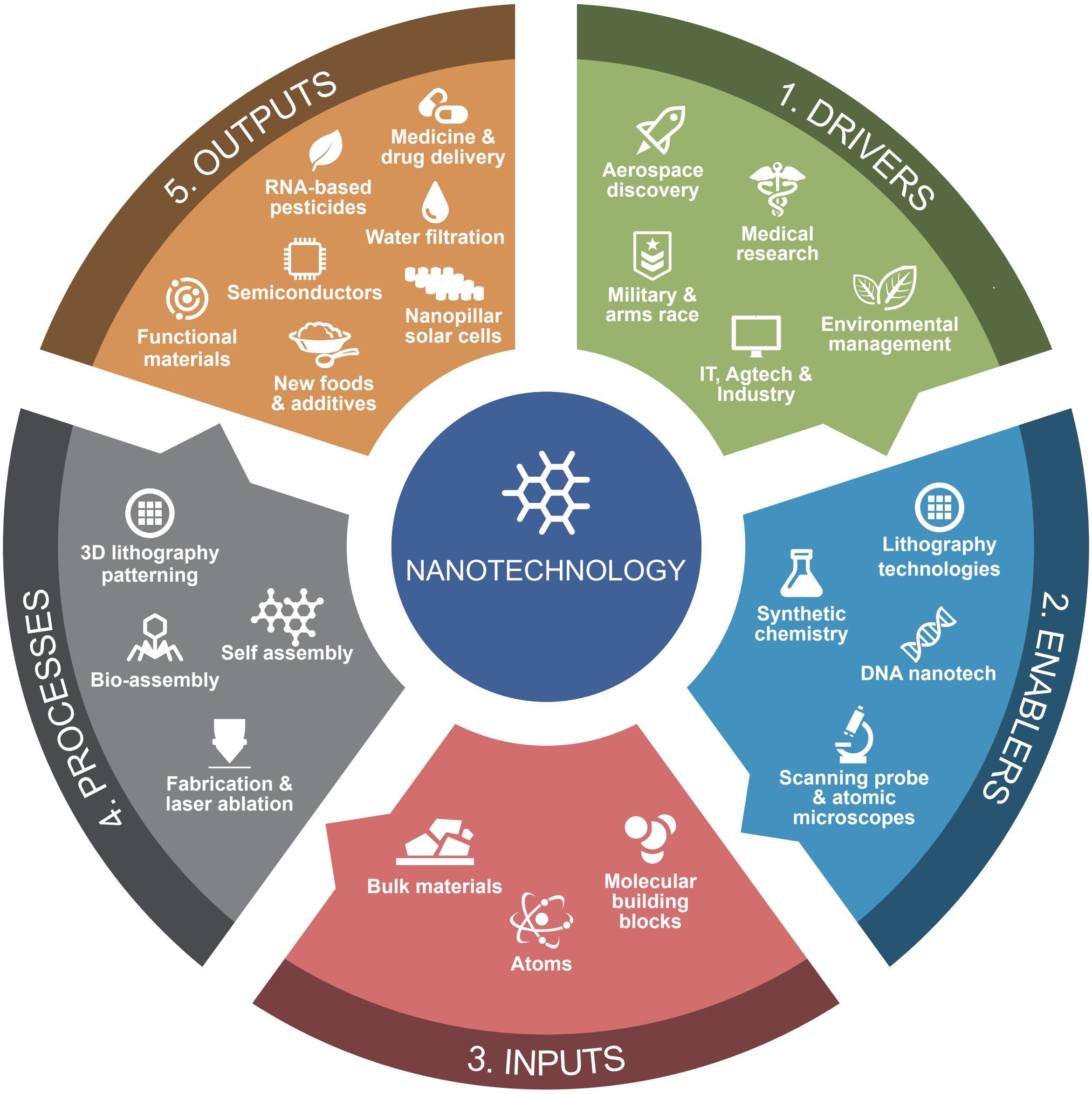
Today, nanotechnology is used to describe our capacity to manipulate materials at that nano scale and encompasses:

nanoscience – advancements in our understanding of the physical, chemical, and biological properties at atomic and near-atomic scales, and

nanotechnologies – which employ controlled manipulation of these properties to create materials with unique capabilities. In many ways, nanotechnology is our attempt to replicate the natural processes, functions and properties of the natural world by emulating those features – as such, nanotechnology is a form of biomimicry.

It is the 'unique capabilities' of these nanomaterials that offer such promise and which have elicited much interest in recent years. For example, using nanotechnology, materials can be made stronger, lighter, more durable, porous, reactive, or residue-repellent, and/or they can be designed as better electrical conductors or to resist wrinkling, or to repel heat better.

Figure 10. Technology and innovation pipeline of nanotechnology



There are already many products on the market and in everyday use which employ nanoscale materials and processes, with applications across medicine, healthcare, industrial products and processes, cosmetics, information technology, and agriculture. Commonly cited examples of contemporary nanotechnology include nanoscale film on eyeglasses, nanoscale additives in fabrics to make them resist to wrinkling, so-called carbon nanotubes used to manufacture lightweight air vehicles, and the use of nanoscale design for drug delivery and new drug therapies. In the agricultural sector, nanotechnology can be used in food processing and packaging, irrigation and water filtration, animal feed, more efficient delivery of animal vaccines, aquaculture, and waste management. With this incredible spread of applications across economic sectors, nanotechnology reflects very neatly the 'technology splitting' phenomenon referred to earlier in this report.

In short, nanotechnology is not one technology – it refers to a vast suite of technologies that have been developed using our recent, highly advanced understanding of subatomic physical, chemical and biological properties which in turn have enabled us to create new materials with enhanced features.

But while the very *smallness* of nanotechnology is what makes its potential so significant, that smallness is also what makes some nanotechnologies so difficult to regulate – **materials behave differently at the atomic level.**

Context

Leaving aside the prevalence of nanotechnology in natural processes, humankind's first forays into the nanoscale date back to the mid-1800s, well before *nano* – was even defined. However the term itself – 'nanotechnology' – was coined in 1974 by the Japanese scientist Norio Taniguchi in a paper describing the separation, consolidation and deformation of materials by one atom or molecule.[2]

Arguably the most strident early advocate for nanotechnology was K. Eric Dexler, the first scientist to receive a PhD in molecular nanotechnology. In the 1980s Dexler envisaged a world where molecular machines and nanocomputers could be used to support the human body's immune system, by being programmed to search out and destroy viruses and cancer cells. But while scientists' interest in the potential for nanoscale science to offer new ways to manipulate the properties of materials dates back to the 1950s, the lack of tools with which to operate at that scale meant little progress was made until the 1980s and 1990s.

Indeed, as with all science, advancements made in nanotechnology have been iterative, with the development of new insights and discoveries, tools and methods providing the building blocks for yet more discovery. For nanotechnology, advancements made in quantum mechanics, molecular biology, organic electronics and a vast array of other scientific fields have seen it evolve from early applications in semiconductors, through to the development of new materials and processes in almost every sphere of life. At the time of writing, there are more than 145,000 patents involving nanotechnology listed with the World Intellectual Property Organisation.

Drivers

Food manufacture – The vast range of applications of nanotechnology correspond with an array of drivers that are encouraging its development. In the agricultural sector, the constraints imposed by resource scarcity and a changing climate, population growth, and shifting markets and consumer expectations, mean the opportunities offered by nanotechnology to improve nutrient delivery and flavour, extend storage life of agricultural products, and allow for the detection of pathogens, toxins and pesticides are especially promising.[3]

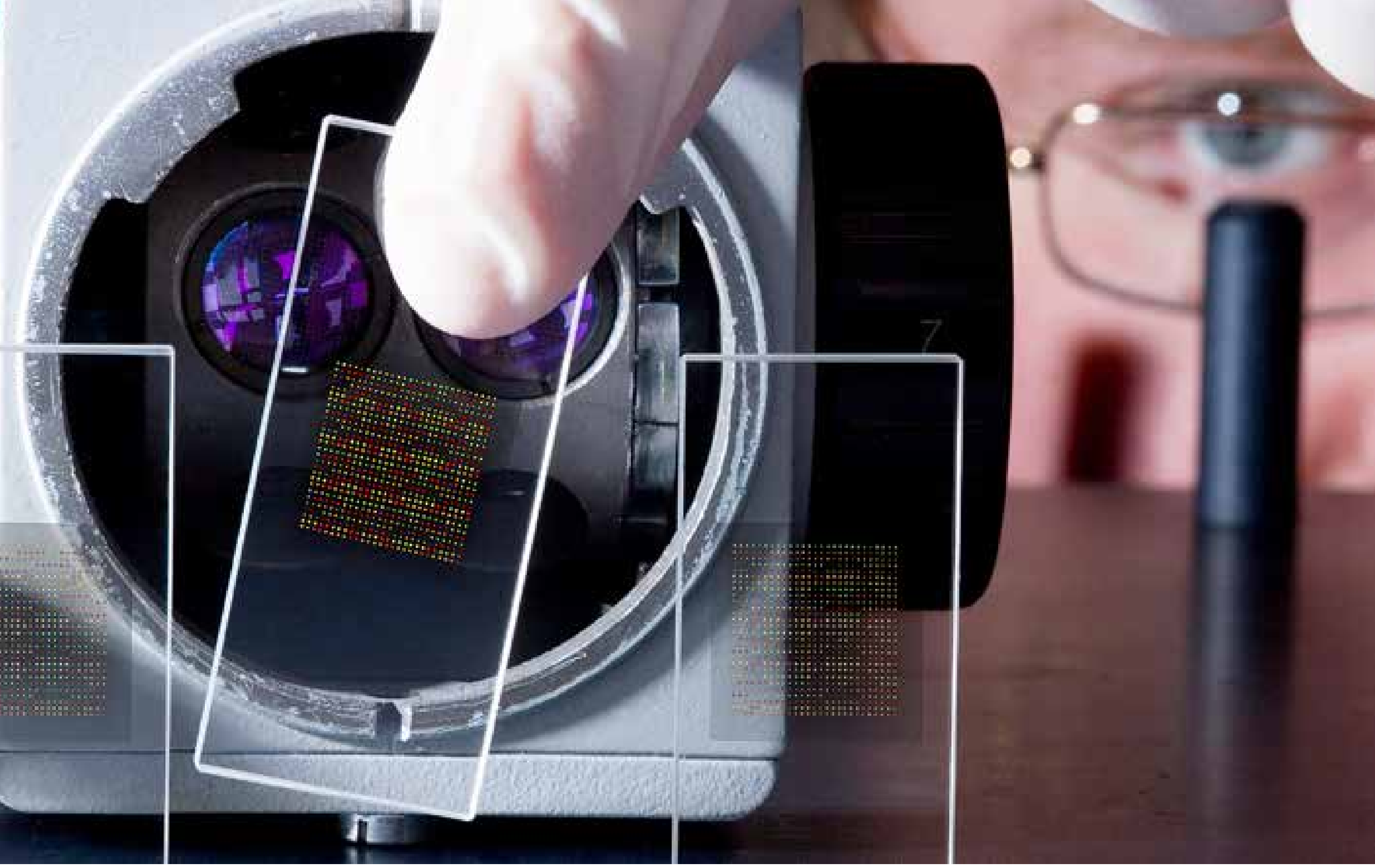
Advanced Manufacturing – The potential to manipulate the properties of materials at the nanoscale is also promising in relation to advanced manufacturing, where durability and energy efficiency are key drivers. For example, some nanotechnologies relate to new types of product coatings or polymers, with one process increasing the strength of steel by as much as 10 times, which in turn means it is more resistant to corrosion. Other nanomaterials can be engineered to increase not only strength, but also temperature and corrosion resistance, while still others can be engineered to provide lubricity and wear resistance. The potential for ultra-lightweight nanomaterials to be used in vehicles, especially aircraft where weight is so critical, is also being explored.

In medicine, the opportunity to exploit nanotechnology to produce more precise and targeted therapeutics could see patients potentially experience shorter and more cost-effective medical treatments. For example, researchers have developed nanoscale electronic devices, sensors and microscopic robots which can travel through the vascular system and target particular cancer tumours.

In the **defence sector,** the potential for nanotechnology is already being realised with new equipment being developed that is stronger and lighter, and in some cases resistant to chemical and biological agents. The defence sector is also developing communications systems that can be woven into specially coated polymer threads in soldiers' garments. The threads can emit light at different wavelengths, thus allowing for silent signalling between soldiers and preventing eavesdropping or detection by enemy units. Ultimately, the drivers behind nanotechnology use in the defence force relate to energy and cost efficiency, and military advantage.

The overall driver, therefore, is the potential to develop more energy and resource efficient products that last longer, cost less over their life cycle, and which consequently offer social, economic and environmental benefits from their development and application.

Those benefits notwithstanding, a key consideration for policy makers, regulators and societies more broadly is the extent to which nanotechnologies *per se* are the most effective means by which to achieve the supposed benefits they offer. For example, if addressing food insecurity is the objective, how significant will the use of nanotechnologies in food packaging be, compared to efforts to genuinely address the underlying economic and institutional constraints that lie at the heart of food insecurity? Somewhat ironically, such considerations strike at the heart of the complexities and contradictions in the drivers behind innovation policy.



Enablers

Microscopy – like many other innovations, the development and application of nanotechnology has been enabled by significant advancements made in many other fields. Crucially, the invention of the scanning tunnelling microscope and the atomic force microscope in the 1980s allowed scientists to see materials at the subatomic level. Without those imaging tools, and indeed those which have subsequently been enhanced in recent years, nanotechnology would not have been possible.

Computational Modelling – similarly, the revolution in information and communications technologies has seen the development of much more powerful computers (supercomputers) which enabled large scale simulations of material systems, in turn providing greater insight into structures and properties of nanoscale materials. Combined with advancements in modelling and simulation, atomic scale visualisation and characterisation, and experimental synthesis, these activities fuelled the contemporary development of nanoscience and nanotechnology.

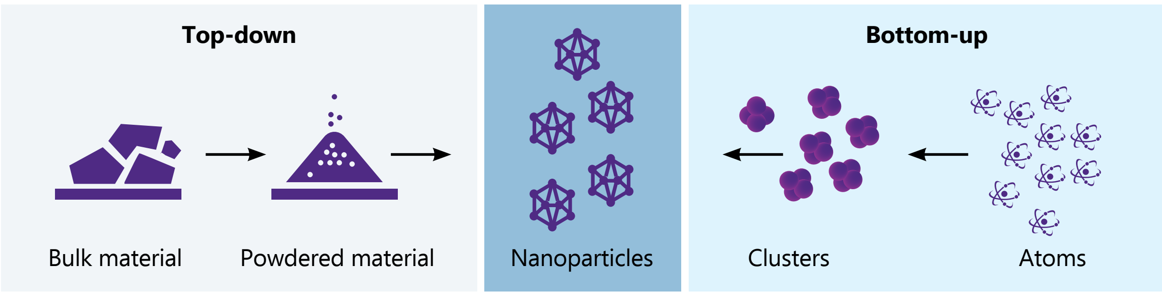
Lithography – a further catalytic advancement in nanoscience was achieved through developments in lithography (a technology originally developed in the eighteenth century), brought about by the extraordinary growth in the semiconductor industry, which in turn saw new techniques for etching, writing, and printing of nanometer-scale structures.

"I think the biggest innovations of the twenty-first century will be at the intersection of biology and technology. A new era is beginning." – Steve Jobs

Inputs

The inputs to nanotechnology are fundamentally not a radical departure from existing biochemical and materials inputs in use today. What is new are the processes and outputs which involve their manipulation at the nanoscale. Thus, the inputs required are simply specialised microscopic and lithographic equipment along with molecular building blocks, nanoparticles and atoms, many of which are in common use in nature or industry already. From a top down approach, the inputs are bulk materials such as graphite, which are thinned down into layers. In this context nanotechnology is a good example of an emerging technology which is process rather than input driven – it is a new way of achieving an end.

Figure 11. Basic schematic of the top-down versus a bottom-up approach to nanotechnology.



Processes

Nanotechnologies are developed using either a top-down or bottom-up approach (**Figure 11**). The top-down approach to fabrication and manufacture is almost like traditional printing – scientists use highly sophisticated tools (photo/optical lithography) to manipulate (using short wavelength light beams or lasers) the atomic and molecular structures of materials to achieve a particular property (greater strength, durability etc.). This method evolved from our experience with manufacturing integrated circuit boards and microelectronic circuit boards, and in very basic terms can be thought of as 'etching' the designed subatomic pattern *in situ*.

Conversely, the bottom-up approach uses chemical or physical forces to encourage the self-assembly of new clusters of atoms and molecules into small building blocks, which build upon one another to create more elaborate structures with the desired properties. Like so many other technological advancements, the bottom-up approach draws on a range of scientific disciplines and approaches, including physics, chemistry, information technology, advanced engineering, metrology and characterisation techniques and biomimetics.

For example, a breakthrough in the emerging field of quantum computer development adopted a bottom up approach to create the world's smallest transistor. In 2010, Australian researchers manipulated individual atoms with extremely high precision, where a scanning tunnelling microscope was used to remove a single silicon atom from a silicon crystal and substitute it with a single phosphorus atom to an accuracy of just 0.5 nanometres.[7]

Considerations for regulators: While the inputs into nanotechnologies are not particularly new or different to past materials production, there are several characteristics and processes unique to nanotechnologies which challenge traditional risk management frameworks and demand attention from regulators. For example, the physical, chemical and biological properties of nanomaterials may differ in important ways from the properties of single atoms, molecules or bulk materials, which makes identifying any direct, indirect and/or cumulative impacts of nanomaterials and nanotechnologies hard to predict. Similarly, the fact that nanoparticles are so small raises concerns about their ability to migrate through organisms and body tissues, which is why the use of nanomaterials in cosmetics, health products, agriculture and food products has been of particular concern for regulators, insurers and consumers.[8] There are also challenges surrounding the impacts of whether a top-down or bottom-up approach is used to fabricate the material, owing to concerns that "subtle changes in the method of preparation can lead to significant alterations in the physicochemical properties and morphologies of the resulting nanoparticles."[9] As such, the need for long term studies to assess the impacts of nanomaterials and nanotechnologies on humans and the environment is needed and such issues are the subject of intense study internationally.

Outputs

There are literally tens of thousands of nanotechnologies either in production or on the market. In the agricultural sector, nanoscience is being used to create new fertilisers, food packaging and coating, and water filtration methods; in the defence sector, lighter and more durable equipment is in development; in the medicine and health sectors, there are new bandages, new drug delivery methods and diagnosis tools on the market; and in the ICT domain, nanoscience is heralding a whole suit of new displays, sensors and semiconductors. For regulators, the challenge is to ascertain the public's level of comfort with different applications of nanotechnologies, and to develop responses which enable the benefits of nanotechnologies to be realised while the necessary science is undertaken to assess the direct, indirect and cumulative risks. It is clear from recent research that consumers are far more comfortable with the use of nanotechnologies in the energy sector, than in the health and medical sectors.

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Recommended further reading

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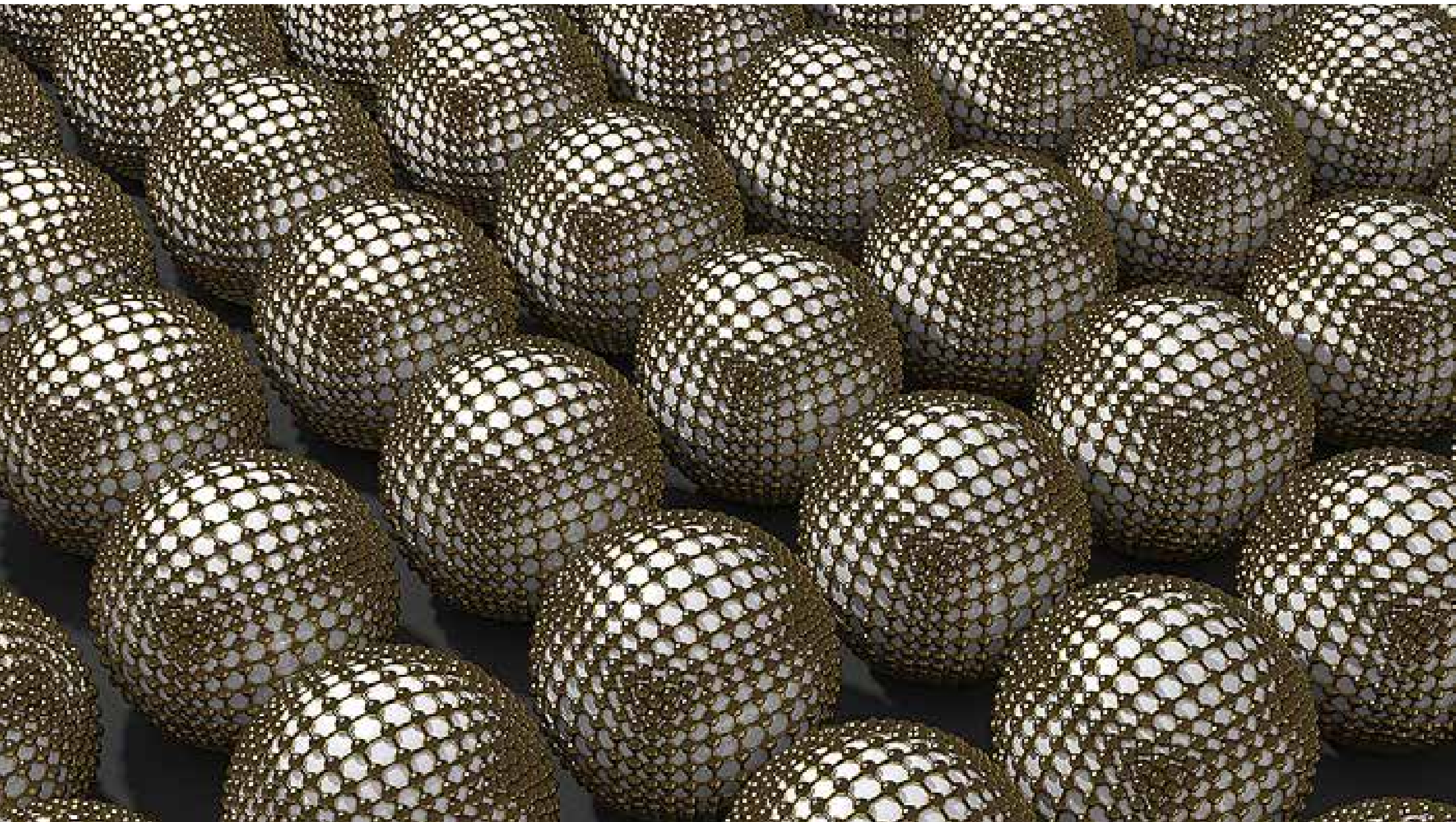
Image: self-assembled mono layers of gold nanocages.



Case Study

(From left) Queensland Alliance for Agriculture and Food Innovation PhD student Elizabeth Worrall, agricultural biotechnologist Professor Neena Mitter and Research Fellow Dr Karl Robinson at UQ's Gatton campus.

BioClay: spray on protection to help address global food challenges

An estimated 795 million people across the globe do not have enough food to lead a healthy life. That's one in every nine people.

It's a sobering statistic, and one that has troubled Queensland Alliance for Agriculture and Food Innovation (QAAFI) agricultural biotechnologist Professor Neena Mitter for years.

"Crop viruses are part of the pest and pathogen burden that reduces global food production by a massive 20 to 40 per cent and, with so many people going without, we simply can't afford for our global food resources to go to waste."

Professor Mitter's team is using nanotechnology and synthetic biology to deliver a non-genetically modified, non-toxic spray combined with clay nanoparticles, co-developed with researchers at the Australian Institute for Bioengineering and Nanotechnology (AIBN), (former UQ) Emeritus Professor Max Lu and Professor Zhi Ping (Gordon) Xu.

Together they have developed BioClay, an agricultural nanotechnology innovation that could help reduce food production losses to pests and pathogens, without the toxic environmental impacts of current chemical sprays or the issues surrounding acceptance and regulation of genetic modification.

BioClay uses a plant defence mechanism known as RNA (ribonucleic acid) interference, or gene silencing, which has been used to develop genetically modified, transgenic, disease-resistant crops.

"This clay is absolutely degradable. The clay left on the surface simply degrades in the presence of natural carbon dioxide and moisture."

Professor Xu's contribution was to develop a nanoscale clay matrix that is ideally suited to prevent disintegration of the unstable double-stranded RNA once it is sprayed onto a crop.

The specially designed matrix forms miniscule, stacked layers that can be compared to puff pastry. These degrade naturally, but in the process they dramatically extend the dsRNA's protection period.

"We were able to provide a delivery vehicle that is loaded onto the plant and can last on the leaf's surface for 30 to 40 days, providing an elongated window of protection," Professor Xu said.

Funded by Hort Innovation and the Cotton Research Development Corporation, the project is delivered by The University of Queensland (UQ) in partnership with Nufarm, and involves trials of the non-toxic, biodegradable product BioClay on farms in Queensland and other locations across the country.

Walter Stahel pointed out that, in nature, there is no waste: discards of water, nutrients, and carbon become resources for others. So too, our business models must follow these principles or else our natural systems will be destroyed.[1]

Circular economy

Definition

Today's production and consumption practices rely heavily on diminishing virgin resources and produce vast amounts of waste in the creation, use and afterlife of products. A circular economy aims to close the loop on these linear pathways by ensuring products, components and materials can be used again in order to minimise waste and maximise the productive value of resources. This regenerative approach can be applied to industrial, agricultural and urban processes.

The Ellen MacArthur Foundation defines the three goals to achieve a circular economy are to:

1. **Design out waste and pollution;**
2. **Keep products and materials in use; and**
3. **Regenerate natural systems.[2]**

Context

Circular concepts are fundamental throughout nature, and they are not new to humans either. Not too long ago, empty milk bottles were collected from homes, washed and reused. Composted food scraps and animal manure provided fertiliser for crops. A broken heating element in a toaster would be replaced at the local repair shop (if you couldn't do it yourself), extending the life of the product.

Rapid industrialisation and market globalisation over the past century has drastically reduced the cost (and perceived value) of goods to such an extent that many items are single-use or discarded more rapidly than in the past.

A poignant example is the rise of cheap 'fast fashion'. From 2000 to 2015, global clothing sales doubled, yet 50 per cent of garments were discarded in less than a year. Not surprisingly, the fashion industry is one of the highest polluters, using 97 per cent virgin feedstock and releasing 1.2 billion tonnes of CO_2 equivalents annually—more than the total aviation and maritime emissions combined.[2]

These systems of waste generation are supported by legacy economic systems that fail to factor environmental costs of a product though its entire life cycle (e.g. waste management and resource depletion) into the final market price. For a long time, the 'business as usual' dogma purported the notion that environmental issues were at odds with economic development. Now, pollution and depletion of resources is causing an economic, social

Figure 12. Circular economy technology and innovation pipeline

and environmental catastrophe to such an extent that it is necessitating a paradigm shift in business practices to sustain future economic development. Cultures and economies of consumerism can be difficult to shift, but clever circular business models can reduce waste and virgin resources to create viable new industries, jobs and markets.

Drivers

Earth's vital systems are under threat – A healthy natural environment provides the foundation for a flourishing society. Human civilisations have thrived in the past 11,000 years due to the very stable climatic and geologic period known as the Holocene.

'Planetary boundaries' define the limits of Earth's vital systems that must not be exceeded to 'operate in a safe space for humanity' (**Figure 8**).[5] Already, we have exceeded the boundaries of nitrogen and phosphorus flows and genetic diversity loss due to the elimination of 60 per cent of all wildlife on earth in the past 50 years.[6]

Reducing Waste – In 2016, two billion tonnes of solid waste was produced globally and projections indicate this will increase by 70 per cent to 3.4 billion tonnes in 2050[7] – almost enough to cover the entire urban area of Los Angeles knee deep in garbage.[i] And that is just one year. Currently, around one third of solid waste goes to landfill, one third is recycled or incinerated, and the remaining third

[i] based on a land area of Los Angeles at 6299 km², a depth of 0.4m and a conversion of 1.3 tonnes of solid waste to one cubic metre in volume.

is dumped on land or in waterways (World Bank Group). Moreover this is only the solid waste and there are further volumes of gaseous and water waste generated in addition to this. This pollution kills wildlife, blocks infrastructure, degrades land, water and air systems, and makes people sick.

Resources are becoming scarce – In 2017, resource use was 1.7 times what the earth could support sustainably. By 2050 that resource demand is expected to double.[8] At these trajectories, many critical resources will be depleted within the century. Increasing demand due to scarcity is increasing the value of both renewables (e.g. timber and crops), and non-renewables (e.g. groundwater, coal, oil, copper, zinc, aluminium, iron, phosphorous, certain rare earth metals), which in turn, makes materials recovery and recycling more economically feasible.

Social license to operate – There is a growing community awareness of the environmental effects of current modes of production and consumption. This has been driven by a range of factors including: media (including social media), NGO campaigns, public debate, education and simply more evidence of pollution encroaching on people's livelihoods and wellbeing. Aware consumers are demanding more 'ethical' products and greater corporate responsibility, transparency and accountability – and often expect the cost to lie with the polluter rather than be passed on to tax payers and future generations. These demands have seen a dramatic rise in 'profit for purpose' businesses, including 20,000 social enterprises in Australia[9], while traditional organisations are also adopting sustainable practices to leverage a more 'green' image for market advantage.

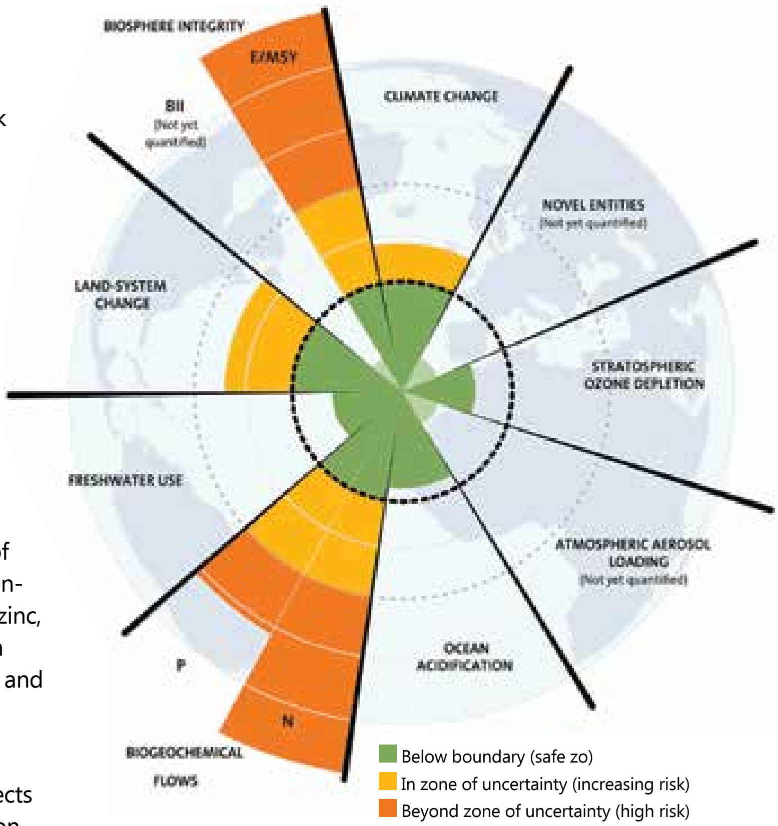


Figure 13. The state of the nine planetary boundaries.

Image credit: J. Lokrantz/Azote based on Steffen et al. 2015.[5]

For example, the New Plastics Economy initiative led by the Ellen MacArthur Foundation[2] has brought together 150 companies including some of the biggest plastic polluters, who have pledged to reduce their plastic footprint through redesigning packaging and developing reuse, recycle and compost models. Among those are The Coca-Cola Company and Unilever who produce three million and 610,000 tonnes of plastic waste per annum respectively. Other organisations leveraging the circular economy movement include Virgin Airlines with its carbon offset program and Google with its circular economy energy efficiency model.

A polluted urban river in the Philippines.

An agricultural drone quadcopter flies over a rapeseed field. Sensors and digital imaging capabilities enable farmers to monitor crop fields and improve production efficiency.

How does a **circular economy** differ from a **bioeconomy?**

Although not synonymous, these two approaches are complementary. The bioeconomy aims to increase the efficiency and sustainability of biological resource use to provide energy and food security, and reduce fossil reliance. Like circular economy, this means minimising waste and managing resources effectively. In this way, many bioeconomy activities are an expression of circular economy principles. The Food and Agriculture Organisation (FAO) define Bioeconomy as: "the knowledge-based production and utilisation of biological resources, biological processes and principles to sustainably provide goods and services across all economic sectors."[3] The FAO further defines its three elements as:

The use of renewable biomass and efficient bioprocesses to achieve a sustainable production

Including for crops, livestock, forestry, aquaculture, fisheries and agro-industries, and replacing, where possible, finite resources with sustainable biomass.

The use of enabling and converging technologies, including biotechnology

Such as genetic engineering of crops and animals to improve yield, industrial microbial processes (e.g. fermentation of foods or expression of therapeutics), and refinery methods to convert waste into value added products.

Integration across applications such as agriculture, health and industry.

For instance, growing algae biomass from nutrient-rich sugarmill effluent as a protein rich animal feed; expression of therapeutics into food products, or biological conversion of plastics into energy.

Enablers

Several critical factors enable circular economies to thrive, these include: government policy, financial settings, new technologies, and development strategies.

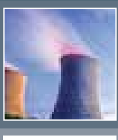
Sorting and recovery technologies are critical to recycle and separate valuable resources from waste but have some way to go. As these technologies proliferate and costs decline, recycling will become mainstream in a wider range of industries. New advanced sorting technologies, such as BioElektra's systems, aim to separate co-mingled household wastes – including aluminium, plastic, glass, paper and food waste – into components that can be reused or resold with up to 96 per cent being diverted from landfill. Other technologies, such as optical sensors are now being used to separate plastics by polymer type and glass by colour – key barriers to recycling plastic and glass.[10]

Converging and emerging technologies such as artificial intelligence (AI), synthetic biology, nanotechnology, and biotechnology are being used to 'design out waste'. For example, machine learning techniques (AI) can rapidly prototype new materials, components and products; while data mining can reveal strengths of circular economy business models, improve equipment performance efficiency, manage and predict stock requirements; and improve the processes to sort and disassemble products, remanufacture components, and recycle materials.[2]

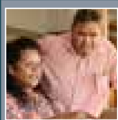
Socially responsible investment (SRI) has become big business. According to a review by the Global Sustainable Investment Alliance (GSIA), in 2017, roughly 25 per cent of professionally managed assets globally, at around US$22.9 trillion in value, included a sustainable investing mandate.[11] These SRIs made up about half of managed assets in Europe and Australia, and between 22 to 38 per cent in the US and Canada.

Eco-industrial parks (EIPs) are enabling companies to go circular by sharing or recycling common resources, so that wastes from some companies can be used as inputs for others. Around 250 such parks exist globally, with China and South Korea leading the way.[12] South Korea's Ulsan Mipo and Onsan Industrial Park is one of the largest EIPs, involving 1,000 companies, 100,000 employees and a US$520 million investment in circular components that has been exceeded with US$554 million in savings.[13] In 2015-16 companies in the EIP reduced 665,712 tonnes of CO_2 emissions, reused 79,357 tons of water, and saved 279,761 tons of oil equivalent in energy use.

How governments can use circular economy principles to their advantage

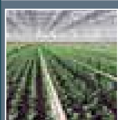


Meet or exceed Austalia's emissions reductions targets set out in the Paris Agreement (26–28 per cent by 2030).

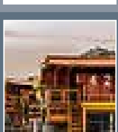


Create new job opportunities to replace jobs lost to automation.

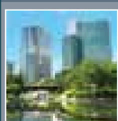
Achieve a number of Australia's United Nations Sustainable Development Goals.



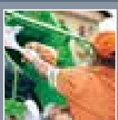
Decentralise and diversify the economy to increase resilience to external shocks.



Manage resource assets responsibly for future generations.

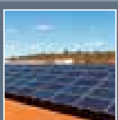


Create cleaner, greener cities.

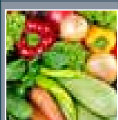


Reduce utilities costs in waste management, water treatment and road infrastructure.

Reduce the economic and social burden of pollution and climate change.



Increase rural and regional development.



Increase food and energy security.

"The Chinese authorities increasingly recognise green finance as an important tool to support the large investments required to build an 'ecological civilization' in China."
– The World Bank[18]

Government policy – many countries are adopting policy frameworks to support a transition to a circular economy. Leading by example are China, Finland, Denmark, Canada and the EU.[14]

Each of these enabling factors can be enhanced by policy and regulation which either support circular economy practices directly, or which reduce the artificial competitive advantage of non-circular practices. Putting a price on waste, pollution and other externalities is critical to provide an even playing field for circular economy initiatives. Current high-waste business practices are artificially supported by being allowed to pollute for free (in the case of greenhouse gas emissions) or at very low cost (in the case of landfill and waste water). Furthermore, the true value of many natural resources such as native forests and rivers are greatly undervalued by excluding the ecosystem services they provide (e.g. filtering water and air, providing habitats, building soil and stabilising the global climate system). Ignoring these 'externalities' promotes an inefficient and unsustainable economic model by artificially subsidising wasteful practices. Building the true cost of pollution and natural assets into financial systems would support circular economy approaches and as an added benefit create a more realistic perception of the cost-benefit equations of resource exploitation. Indeed, many circular economy processes are already the most cost-effective option when true costs are considered. However, no economic system can truly reflect the irreplaceability of the natural environment and its inherent value to life, so regulation is essential.

As with any economic change, impacts on existing industries and communities must be managed to ensure a rapid and sustainable transition. However, it is part of the purpose of circular initiatives to displace harmful features of some conventional industries.

Inputs

Circular economy is an innovative concept rather than a specific technology, so it requires a wide range of different inputs depending on the industry or product it is applied to. In general, waste products are the key resource that is fed into the system. Biological waste includes food and green waste, manure, meat and animal by-products. Some funeral services are even offering to turn your human loved one into compost. Industrial and post-consumer waste includes plastics, paper, tin, metals, minerals, ceramics, glass, cement, and by-products of manufacturing and mineral processing. Liquid wastes are grey water, sewage, industrial wastewater. Waste heat energy from industrial processes can also be harnessed and used productively. Each of these waste streams can provide a valuable input for circular economy processes. With an endless supply of waste, there is enough input for everybody.

In addition to their benefits, policy makers and regulators must be aware of the potential health and environmental risks of using waste materials. Many waste products contain toxic contaminants which are hazardous to handle. Biological waste can be especially harmful to human health and new protocols must be developed when using it in circular processes.

Processes

Strategic circular economy initiatives prioritise actions according to their effectiveness in reducing waste and consumption of virgin resources. Most effective is to avoid and reduce consumption in the first place, followed by reusing products and materials as many times as possible. Still valuable, but less effective is recycling waste material into new products and ensuring new products contain recycled content. In many cases it is possible to recover energy from biological waste which can reduce greenhouse emissions, although this does not prevent the material from being lost. As a last resort, a minimum amount of waste can be disposed of safely.

Circular economy initiatives are very diverse, so innovators and policy makers must employ a wide range of strategies to support and manage them. These include innovative business models, new technical processes and even new (or resurgent) cultural attitudes to consumption. Policy and regulation play a critical role in supporting each of these models.

Imagine no possessions: collaborative consumption, sharing and services – perhaps this is not what John Lennon envisaged when he penned his famous song lyric, but here we are – a world where a US$8 billion equity-funded company facilitates travel, yet owns no vehicles and the largest accommodation service provider owns no real estate. A number of businesses are turning away from reliance on product sales and moving toward business models favouring **product-service**

systems (PSS) and **sharing of goods**. Companies can benefit by reducing costs of replenishing stock and adding value for their clients, while consumers are liberated from the burden of ownership. The centrality of these models is that most goods lie dormant for much of the time, therefore their value can be maximised when shared to create an 'access economy' or 'on-demand economy'. These goods may be privately owned by individuals but facilitated by digital platforms (e.g. Airbnb and Uber), or may be owned by companies and rented or leased. The latter can ensure whole-of-life stewardship over a product as it incentivises providers to invest in robustness, reuse and maintenance rather than planned obsolescence.

However, the **regulatory fuzziness surrounding private versus business-type transactions** is raising significant issues relating to taxation, employee rights, and oversight; as well as causing impacts to existing markets and having social implications for liability, rights and responsibilities of the facilitator, individual service provider and the consumer (see case study).[15]

From trash to treasure: re-commerce and refurbish – unwanted goods are big business in Australia. According to a Gumtree Report in 2018, our second hand goods economy was worth AU$34 billion and Australia tops the list of nations for owning the most unwanted or unused goods. A number of digital platforms, re-sellers and social enterprises are emerging to re-commerce these goods back into circulation and reduce the demand for new products. Gumtree, Ebay and Facebook Marketplace are dominating the digital market, allowing their customers to buy and sell second hand goods, often much cheaper than new items. Similarly, value is being found in refurbishing, repairing and selling refurbished items, keeping resources in circulation for longer and reducing landfill. This also places demands on manufacturers to ensure products can be serviced easily and affordability.

The circle of life: the bioeconomy model – seeks to close the loop on organic waste in four ways:

1) Reducing food waste, as at present Australians throw away over three million tonnes of food, worth AU$20 billion each year. Social enterprises such as OzHarvest and FoodBank are 'rescuing' food otherwise destined for landfill, with proceeds helping communities.
2) Using biorefinery methods, either thermal or catalytic, to turn biowaste into valuable products. For instance, refining crop residues and food waste to biogas for use as a fuel source.
3) Using biosequestration methods to remediate nutrients from waste and turn it into biomass. For example maggot farms use meat waste where harvested maggots are used for fish feed, or algae is used to treat wastewater and the biomass is used for biofuels.
4) Using biodegradation methods such as composting and anaerobic digestion to break down organic components to their molecular building blocks which can then be used for biofertilisers.[16]

A growing number of leasing and subscription services offer users flexibility and convenience, without the hassle of ownership. Image courtesy of Tourism and Events Queensland.

Circular by Design – Designing products in a circular economy requires consideration of the full life cycle such that components can be easily refurbished, repaired, reused or recycled after use. Cradle to cradle designs (as opposed to cradle to grave) can enable companies to retrieve resources from their customers after use and may benefit from upselling or upgrading items.

"A strong circular economy begins at the design stage ... the challenge is to design products and technology with regeneration in mind right from the beginning, without ever sacrificing performance." – Chris Adam, Google Supply Chain Manager.[17]

Outputs

Circular economy principles are incredibly flexible and can be applied across all sectors and industries. The examples below provide a glimpse at the valuable outputs and new innovations already being produced from circular economy initiatives.

Rental and subscription services can liberate users from the costs and maintenance of ownership and provide greater flexibility. Update and upgrade to the car you want with car subscription services such as Carly. In cities, a range of mobility service businesses, such as Lime, are popping up, offering short-term rentals of electronic scooters, bikes and transit vehicles using app-based subscription services. Clothing subscription services such as Style Theory enable subscribers to update their wardrobe with high-end brands each month with the subscription and return based service, while VIGGA offers exchange of children's clothing as they grow. Appliance and equipment rentals such as Warehouse of America offer servicing and exchange.

Second hand goods may not have the same sparkle as new items, but they allow thrifty consumers the opportunity to purchase high end brands at a fraction of the cost. In the fashion space, ThredUp is one of the largest online resellers of women's and children's clothing, where consumers can buy major brands at a fraction of the cost of buying new.

Eco-friendly goods produced from recycled or sustainable materials have a lower environmental footprint, offering environmentally-conscientious consumers peace of mind.

Refurbished goods can allow companies to resell goods at discounted prices while avoiding waste. For example, many tech firms, from small businesses to global giants refit and resell computers after use.

Recycled goods can be produced from waste which would otherwise become landfill or pollution. For example, rubber tyres create a huge waste burden as they are non-degradable, have a high volume, and are chemically difficult to reuse. In Australia, an estimated 56 million tyres reaching their end of life each year in Australia. The Tyre Stewardship Australia is helping to create value chains involving tyre manufacturers, mechanics, resource recovery centres and business that use recycled rubber. Recycled rubber is now finding a number of uses in building materials, rubberised asphalt for roads, wall barriers and footwear.

At the design stage, Johnson Controls has designed a battery that is 99 per cent recyclable, an incredible feat for a product so chemically complex and hazardous. By encouraging consumers of conventional batteries to recycle, the company received enough material to prevent hundreds of millions of batteries from ending up in landfills.

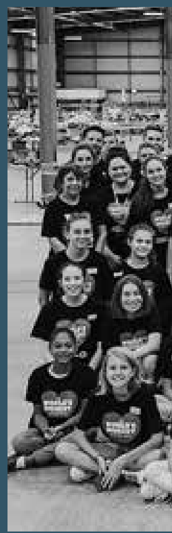
Bio-products can be produced from biowaste and reused within human production system, examples include reuse of treated waste water or the production of biofertilisers. The Finnish company Aquazone has developed a method of upcycling wastewater into fertiliser. The wastewater is treated biochemically, and solids, water, and nutrients are separated. The water can be used for irrigation or can be further recycled into drinking water; the sludge is nutrient-rich and can be used as an organic fertiliser.

Homegrown: Some of the best Queensland

World's Biggest Garage Sale: re-homing dormant goods

Business model: re-commerce, volunteer networks, profit-for-purpose

What began as a one-off event to raise money for children's cancer research, the Brisbane-founded social enterprise has now become a model for circular business that will soon be adopted by other cities around Australia and, possibly, abroad. Founded by Yas and Leigh Grigaliunas, the World's Biggest Garage Sale events have re-commerced 3.3 million kg of household dormant goods and raised $314,000 for children's charities.



Substation 33: re-purposing e-waste

Business model: recycle, re-furbish, re-manufacture, skills training

This social enterprise based in the Logan region is on a mission to divert electronic waste from landfill. Its services include e-waste collection, processing and audits, data destruction, and the resale of refurbished computers for as little as $100. They also provide skills training to interns and volunteers wishing to start a career or gain experience in e-waste recycling, IT, 3D printing and software or hardware development. Their innovation lab and team of technical specialists are also developing and commercialising innovative products and services from e-waste such as electric bikes, flood warning road signs and 3D printers.

AATLIS: food & fibre innovation

Business model: bioeconomy, eco-industrial park, industrial symbioses, resource sharing

The new 160 ha AATLIS precinct, located in the agriculture rich Toowoomba region, will be a world class hub for sustainable and profitable pathways for food and fibres. The industry-led development, founded by FKG group, will bring together complementary businesses to create productivity gains at every step of the agri-food value chain through digital technology adoption and circular economy collaboration.

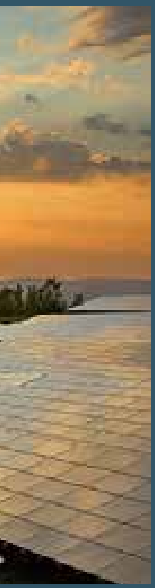
We would like to thank the Department of Environment and Science, Queensland Government for providing these examples.

projects pioneering the circular movement

Brisbane Tool Library: activating dormant goods

Business model: sharing service

This local start up was founded by Sabrina Chakori on the premise that most tools in the home lie dormant most of the time, often being used on average just minutes per year. The 'library of things' allows users to lend and borrow a range of tools, and other goods such as camping and sporting equipment, liberating the need for ownership and increasing the purpose of goods.



The RAPAD Big Vision: for regional development

Circular strategy: regional planning, renewable energy, bioeconomy, water recycle

The Remote Area Planning & Development Board (RAPAD) represents seven Central Western Queensland shire councils with a population of ~10,000 people. It's forward looking 'Big Vision' roadmap outlines six circular economy principles to transform the region into a self-sustaining producer and exporter of goods and services. The strategy seeks to leverage the region's local knowledge, vast land and agricultural capacity to develop renewable energy, manufacture water, produce food, create an advanced industry, and expand international services.

Yarrabilba: a vision for circular communities

Circular strategy: community planning, education and community engagement, smart monitoring

Lendlease's vision for Yarrabilba in the Logan region is to become Australia' first circular economy master planned community. The Circular Economy Lab will trial a service-based business model designed to reduce energy use and promote behavioural change in its residents. Other organisations involved with the project include RACQ, Fisher and Paykel, Coreo, Access Community Services and Movus, as well as Substation 33.

Recovered energy can be produced from a number of already existing industrial processes. Examples include converting landfill gas into energy; using sugarcane waste products to fuel power plants in North Queensland; and heat recovery ventilation systems which recover heat from outgoing air to keep buildings warm in cold climates. Emerging industries are producing electricity or liquid fuels (ethanol and diesel) from food waste, microalgae and anaerobic sludge and industrial by-products.

Recovered metals from e-waste are often highly valuable and can be reused in new electronic goods or other applications. The Brussels-based company Umicore extracts gold and copper from electronic waste and Swiss firm Batrec removes zinc and ferro-manganese from batteries. Presently these processes are energy-intensive and only partly recover the metals. To close the recovery loop we will need new technologies to separate materials which are fused through polymers, alloys, lamination and coatings.

Some circular processes may deliver variable quality and consistency of recycled products due to variations in feedstocks. In some cases, product standards may have to be adjusted to allow for this level of variation. This is particularly important for safety standards which were developed without circular economy processes in mind.

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Sharing is Not Always Caring:

Regulatory Issues of Alternatives to Car Ownership

The pernicious effects of mass car ownership are increasingly being recognised in the early twenty-first century; ranging from congestion and pollution through to being a major contributor to green house gas (GHG) emissions. As a consequence, a number of schemes such as congestion charges, and pedestrianised zones have been introduced, primarily in cities, with the aim of addressing some of these concerns. An alternative would be to reduce the need for each individual consumer to own their own car, again especially in urban areas where they may not use their car every day. This possibility has been enhanced by the rapid spread of digital technologies (in particular smart phones) which are allowing consumers to connect to alternatives to car ownership such as ridesharing and renting.

In the former, a driver is contracted by a firm (such as Uber) through which the consumer books a trip, like a traditional taxi-cab, unlike a taxi however the firm need not own the vehicle in which the consumer travels. Renting firms (such as Car2Go) are more similar to existing rentals firms, however their cars are not stored in a centralised location and instead once the consumer rents one, they may collect it from a (hopefully) nearby street location. Both of these alternatives are promoted as serving a public good in removing vehicles from the road and thus reducing the aforementioned effects of mass car ownership.

That said there are numerous issues for regulators arising from both ridesharing and rental platforms which, if not met, may pose serious risks to the public good. Overall, rental services pose less difficulty as they are more similar to conventional rental models, simply being accessed via smart phone and with vehicles (still owned by the company) diffusely distributed. However many rental platform vehicles are parked on public roads which are funded by taxpayers and hence there is a concern that rental platforms may be monetising public space for profit without fair recompense to the taxpayer. Secondly, the demographic of rental use may mean that their impact on car usage is likely to be reduced or overstated. The consumers with the greatest access to rental vehicles and who are less likely to use cars every day, are more likely to live in urban areas already served by effective public amenities and, therefore, they are less likely to own or use a car as it is. Consequently, rental platforms may not reduce car ownership by as much as hoped, as many consumers in the target demographic are less likely to own a car under business-as-usual circumstances.

Nevertheless, the regulatory challenges of rental services pale in comparison to the difficulties created by ridesharing. Many disruptive firms (including the ride-sharing service Uber) do not classify their drivers as employees, arguing that they simply provide a platform through which independent drivers operate and link to consumers. Regardless of the legal accuracy of this position, it ought to raise regulators' concerns over the potential for firms to evade public good regulation (health and safety, workers' rights, etc.) under the guise of being disruptive. Moreover it is an open question whether such a new take on employment contracts ought to be considered innovation or a regression to the nineteenth century. Besides the negative consequences of ridesharing for its own drivers, it also poses a difficulty to existing traditional firms which are forced to compete with a new firm which may have fewer overheads due to its weaker employment model. These existing firms are socio-economically embedded in surrounding communities and allowing the law to drive them out of business may create unfair economic collateral damage.

Finally, from a public good perspective governments must ask whether either ridesharing or rental platforms offer a superior alternative to investment in public utilities such as public transport, or cycling infrastructure. The more these new services grow (and profit) the less consumers may be willing to pay for public amenities they do not use, yet if the goals of reducing car ownership are to curtail pollution, GHG emissions, and congestion then public infrastructure may offer a better alternative than either rental or ridesharing platforms.

Christopher McEwan, Centre for Policy Futures

Glossary

Algorithm	A step-by-step procedure for solving a problem. It is used for calculation, data processing and automated reasoning. An algorithm can tell a computer what the author wants it to do, the computer then implements it, following each step, to accomplish the goal.
Anticipatory regulation	An emerging approach that is proactive, iterative and responds to evolving markets.
Artificial intelligence	The theory and development of computer systems that can do tasks that normally require human intelligence. This includes decision making, visual perception, speech recognition, learning and problem solving. Current AI systems are capable of specific tasks such as internet searches, translating text or driving a car.
Big data	The diverse sets of information produced in large volumes and processed at high speeds using AI. Data collected is analysed to understand trends and make predictions. AI can automatically process and analyse millions of data-sets quickly and efficiently and give it meaning.
Bioeconomy	Aims to increase the efficiency and sustainability of biological resource use to provide energy and food security, and reduce fossil reliance.
Bioengineering	1: the application of engineering principles, practices, and technologies to the fields of medicine and biology especially in solving problems and improving care (as in the design of medical devices and diagnostic equipment or the creation of biomaterials and pharmaceuticals). 2: the application of biological techniques (such as genetic recombination) to create modified versions of organisms (such as crops).
Bioinformatic	The science of collecting and analysing complex biological data such as genetic codes.
Biometrics	The application of statistical analysis to biological data.
Biomimicry	The imitation of natural biological designs or processes in engineering or invention.
Circular economy	An alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life.
Data mining	The practice of examining large pre-existing databases in order to generate new information.
Deep learning	A subset of machine learning where artificial neural networks and algorithms inspired by the human brain learn from large amounts of data.
e-waste	Waste consisting of discarded electronic products (such as computers, televisions, and cell phones).
Gene	A specific sequence of nucleotides in DNA or RNA that is located usually on a chromosome and that is the functional unit of inheritance controlling the transmission and expression of one or more traits by specifying the structure of a particular polypeptide and especially a protein or controlling the function of other genetic material.

Gene drive	A gene drive is a genetic engineering technology that propagates a particular suite of genes throughout a population by altering the probability that a specific allele will be transmitted to offspring from the natural 50 per cent probability.
Gene technology	The term given to a range of activities concerned with understanding gene expression, taking advantage of natural genetic variation, modifying genes and transferring genes to new hosts.
Genomic data	Also known as biodata, refers to the genome and DNA data of an organism.
Internet of Things (IoT)	The ability of any device with an on and off switch to be connected to the internet, and send and receive data.
Machine learning	The scientific study of algorithms and statistical models that computer systems use in order to perform a specific task effectively without using explicit instructions, relying on patterns and inference instead.
Nanomaterial	A material having particles or constituents of nanoscale dimensions, or one that is produced by nanotechnology.
Nanotube	A microscopic tube whose diameter is measured in nanometers.
Nanoscience	The study of structures and materials on the scale of nanometers.
Nanotechnology	The manipulation and manufacture of materials and devices at the 'nanoscale'.
Piggybacking	Where two technologies are combined to either accomplish a new task or to increase the efficiency of one or both.
Regulatory divergence	Inconsistent regulation between different jurisdictions.
Synthetic biology	The design and construction of new biological entities such as enzymes, genetic circuits, and cells or the redesign of existing biological systems.
Technology convergence	The layers of abstraction that enable different technologies to interoperate efficiently as a converged system.
Technology splitting	The capacity for a technology to rapidly proliferate into new applications in ways that are hard to anticipate.

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