Chapter 11

ARTIFICIAL INTELLIGENCE, BLOCKCHAIN AND QUANTUM COMPUTING

KEY FINDINGS

- By June 2020, over 60 countries had developed a national AI strategy or policies on AI and others were following. Countries were promoting AI research and development, data access and skills. At the same time, they were exploring approaches to ensure trustworthy AI and to mitigate risks associated with AI systems.
- Investment and research on artificial intelligence (AI) have been growing fast in recent years. The total number of AI-related scientific publications quadrupled over 1999-2019, mainly driven by the United States, the People's Republic of China (hereafter "China") and the European Union. AI-related scientific publications co-authored by the United States and China more than doubled between 2014 and 2020.
- Countries are using AI tools widely to help monitor and predict the spread of COVID-19 in real time, speed diagnosis and search for treatments at an unprecedented pace and scale.
- Distributed ledger technologies (DLTs) offer a new way of securing data and transaction records for use by multiple parties without reliance on a trusted, central authority. Among DLTs, blockchain has gained fast notoriety in financial markets. However, countries are developing DLT-based solutions in a wider range of activities, including transport, energy and government services.
- Several countries (e.g. Australia, China, Germany, India and Switzerland) have recently issued some blockchain strategy, while others (e.g. France and Italy) are developing it. International initiatives, like the OECD Blockchain Policy Centre, aim to help governments better understand this technology, address the challenges raised by DLTs and their applications, and seize opportunities to achieve policy objectives and deliver more effective government services.
- Quantum computing brings the promise of addressing computational problems that are intractable on any classical computer. It could also accelerate innovation in a wide range of areas, including agriculture, drug development and energy, as well as auto and airplane manufacturing.
- Research on quantum technologies is a global field. The three leaders are the United States (quantum computing), Europe (quantum mechanics) and China (quantum communication and cryptography).

Introduction

This chapter explores three technologies that are – or have the potential to become – key drivers of digital transformation: artificial intelligence (AI), distributed ledger technologies (DLTs) and quantum computing.

AI has risen to the top of the innovation and policy agendas of many OECD countries and partner economies. AI tools are being used widely to help monitor and predict the spread of COVID-19 in real time, speed diagnosis and search for treatments at an unprecedented pace.

DLTs offer a new way of securing data and transaction records for use by multiple parties without reliance on a trusted, central authority. Among DLTs, blockchain has gained notoriety following its rapid diffusion in financial markets. However, countries are developing a wider range of DLT-based solutions to facilitate access to finance by small and medium-sized enterprises (SMEs), allow better integration of transport services, improve efficiency in the public sector and develop low-carbon infrastructure models.

Quantum computing brings the promise to increase computing capacities enormously and address problems that are intractable on any classical computer. In particular, it is expected to accelerate research and innovation in agriculture, drug development and energy, as well as in auto and airplane manufactures. At the same time, quantum computing may be able to break many current cryptography methods.

Artificial intelligence

While the development of national policies on AI is relatively new, countries have set ambitious targets. This section examines trends in national AI strategies and policies, which aim to support innovation and the development and adoption of AI systems that are trustworthy and human-centred. It builds on data and evidence from the OECD AI Policy Observatory (*www.oecd.ai*). AI policy initiatives are structured according to the 2019 OECD *Recommendation of the Council on Artificial Intelligence* (hereafter "the OECD AI Principles") (OECD, 2019[1]). First, they draw on the five values-based principles for the responsible stewardship of trustworthy AI. Second, they refer to policy recommendations pertaining to national policies and international co-operation for trustworthy AI.

AI promises to increase the efficiency and effectiveness of entire sectors, including the delivery of public services. Applied wisely, AI can improve well-being in areas like education, public safety and health. It can also help address pressing global problems, such as climate change and wider access to health care and mobility. Governments are planning to invest in and develop AI for its many benefits.

Yet alongside benefits, AI raises new or heightened types of ethical and fairness concerns. Chief among them are questions of respect for human rights and democratic values, and the dangers of transferring biases from the analogue into the digital world. Designing systems that are transparent about the use of AI and accountable for their outcomes is critical. AI systems must function properly and in a secure and safe manner.

National AI policies must build on international agreements. Over 40 governments signed up to the OECD AI Principles in May 2019, thereby agreeing to ensure trustworthy, human-centred AI systems. National policies are needed to put these principles into action, including those that encourage investment in responsible AI research and development (R&D).

In addition to AI technology and computing capacity, AI leverages vast quantities of data. This increases the need for a digital environment that enables access to data, alongside strong personal data and privacy protections, notably for systems that use sensitive personal data.

AI-enabling ecosystems can also support SMEs as they navigate the AI transition and ensure a competitive environment. AI will change the nature of work as it replaces and alters components of human labour. Policies will need to facilitate transitions as people move from one job to another, and ensure continuous education, training and skills development.

While approaches differ, national AI policies aim to serve all of society

In 2017, Canada became the first country to launch a national AI strategy. By April 2020, more than 60 countries had national AI policies and others were following suit. Italy was the most recent country to adopt a national AI policy in July 2020.

Some countries included policies for AI within their broader digital strategies. Countries such as Korea, Spain and the United States created AI R&D strategies. A few countries, such as China, France, the Russian Federation and the United States focused part of their AI strategies on the defence sector. The European Union's Co-ordinated Plan on AI of December 2018 encouraged member states to set up national AI strategies outlining investments and implementation measures.

National AI strategies and policies have ambitious targets. However, they differ in terms of objectives, timeframe for implementation, budgets and associated policy instruments for implementation (Figure 11.1). They articulate priorities for public investment and public R&D on AI, sectoral focus, education and employment, regulation and international co-operation. At the same time, national AI policies consider AI-related risks and challenges. Many countries have issued ethical guidance for AI systems and are reviewing and adapting policy and regulatory frameworks.

Effective implementation of national AI initiatives hinges on co-ordination

Different countries are pursuing varying national governance approaches to co-ordinate implementation of their national AI policies across government and offer regulatory and ethical oversight:

- Government or independent bodies co-ordinate implementation of national AI strategies in several countries. France co-ordinates AI within the Prime Minister's Office; the United Kingdom has an

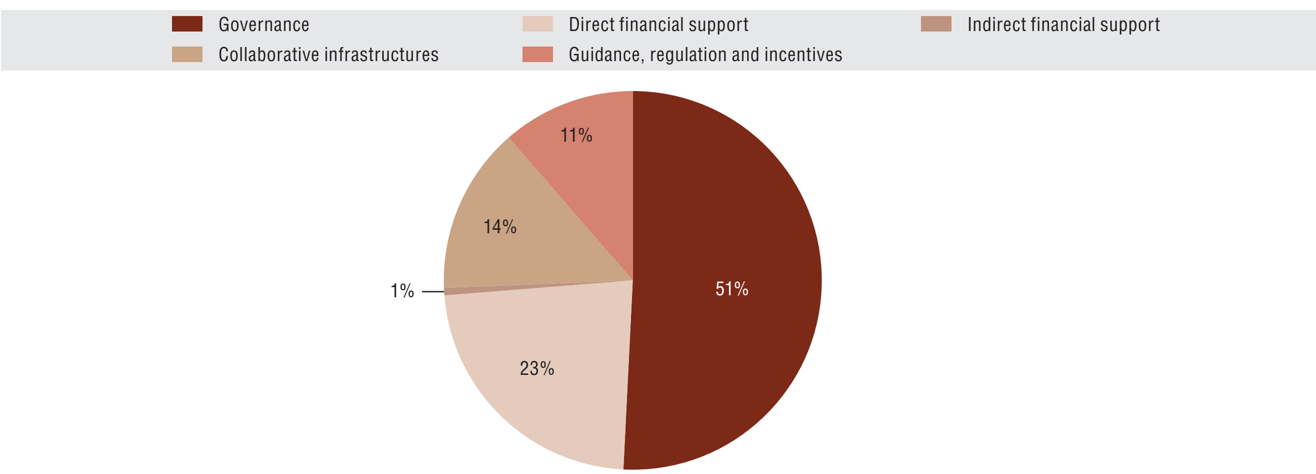
Office for AI; the United States has an AI Interagency Working Group; Egypt has a National Council for Artificial Intelligence headed by the Minister of Communications and Information Technology; and the Canadian Institute for Advanced Research co-ordinates implementation of Canada's AI strategy.

- Expert advisory bodies conduct technology foresight and impact assessment on AI in work and society and provide recommendations to the government. These include Austria's Council on Robotics and AI; Canada's Advisory Council on AI; Spain's Artificial Intelligence Advisory Council; the United Kingdom's AI Council; and the United States' Select Committee on AI under the National Science and Technology Council.
- Some countries have oversight and advisory bodies. These include the Data Ethics Advisory Group in New Zealand, the United Kingdom's Centre for Data Ethics and Innovation, and Singapore's Advisory Council on the Ethical Use of AI and Data.

The design of most national AI strategies underwent formal public consultations and involved numerous stakeholders, including key industry consortia, academia, trade unions and civil society.

Figure 11.1. Policy instruments used in national AI policies, 2020

By type



Note: Data refer to a total of 538 policy instruments used by 60 countries, including the European Union. StatLink contains more data.

Source: OECD AI Policy Observatory, *https://oecd.ai* (accessed in April 2020).

StatLink https://doi.org/10.1787/888934192832

Countries have begun to monitor implementation of AI policies

Countries such as Canada, the United Kingdom and the United States have started to conduct policy intelligence activities and issue annual reports to evaluate implementation of their national AI strategies.

In addition, to oversee implementation of national AI strategies and policies, a few national or regional institutions have established AI observatories. For example, Germany's Labour Ministry launched the KI-Observatorium in March 2020. It aims to help implement parts of Germany's AI strategy and encourage the responsible, people-centred and participatory use of AI in the world of work and society. Other observatories include Quebec's International Observatory on the Social Impacts of Artificial and Digital Intelligence in Canada; France's Observatory on the Economic and Social Impact of Artificial Intelligence; the Italian Observatory on Artificial Intelligence; and the Czech Republic's AI Observatory and Forum.

The European Union has planned joint monitoring to take stock of accomplishments and evaluate potential actions for next year's co-ordinated plan. AI Watch is a joint programme of DG Connect and the Joint Research Centre (JRC) to monitor and evaluate the uptake and impact of AI in Europe. They are developing indicators with member states to calculate, monitor, target and assess investments proportionally. In February 2020, the OECD launched the AI Policy Observatory (OECD.AI),[1] a platform for policy makers to monitor developments in the AI policy landscape. Among other features, the Observatory includes an open and comprehensive database of AI policy initiatives, regularly updated in collaboration with the JRC.

Most national AI policies focus on a handful of sectors, including health care and mobility

National AI strategies and policies outline how countries plan to invest in AI to build or leverage their comparative advantages. They also encourage businesses to develop solutions that will boost growth and well-being. Countries tend to prioritise a handful of economic sectors, including mobility – logistics and transportation – and health (Table 11.1). In mobility, AI applications can help governments improve road safety, enhance public transportation efficiency, manage traffic and reduce carbon emissions. In health care, AI can help governments harness the latest breakthroughs to help detect health conditions early or remotely. They can also help deliver preventive services, optimise clinical decision making and discover new treatments and medications (OECD, 2020[2]). The OECD's Committee on Digital Economy Policy has created the OECD Network of Experts (ONE AI). As a major part of its role, ONE AI analyses the pros and cons of focusing national AI policies on specific sectors and/or of adopting horizontal approaches.

Table 11.1. Countries' AI policies focus on a handful of sectors, selected countries

Sector(s) targeted	Australia	Czech Republic	Denmark	France	Finland	Japan	Netherlands	Norway	Sweden	United Kingdom	United States	China	India	Singapore	Turkey	Malta	Saudi Arabia	United Arab Emirates
Agriculture and food	✓		✓				✓				✓	✓	✓		✓			
Cybersecurity						✓								✓	✓			
Defense/security				✓					✓		✓	✓		✓	✓			✓
Education		✓				✓					✓		✓	✓	✓	✓		
Energy			✓		✓			✓		✓	✓	✓				✓	✓	✓
Environment	✓			✓			✓			✓	✓						✓	
Health care	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Manufacturing						✓			✓	✓	✓				✓		✓	
Mobility and transportation		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Productivity					✓	✓									✓			
Public administration				✓	✓	✓		✓							✓	✓		
Seas and oceans								✓										
Smart cities	✓								✓				✓		✓		✓	✓
Space		✓									✓							
Telecommunications						✓					✓				✓	✓		

Note: The Pan-Canadian AI Strategy and the German AI strategy do not have a significant focus on specific sectors.

Source: OECD AI Policy Observatory, *https://oecd.ai* (accessed in April 2020).

AI promises to make government services "smarter": more agile, efficient and user-friendly. For instance, AI can help deliver personalised services to citizens. It can also enhance the efficiency and quality of administrative procedures by automating physical and digital tasks. In addition, it can improve decisions through better predictions based on patterns in large volumes of data (Ubaldi et al., 2019[3]).

Building on their digital government approaches, many national AI strategies and policies explicitly encourage adoption of AI in the public sector. For example, the EU Co-ordinated Plan on AI plans to "make public administrations in Europe frontrunners in the use of AI". Denmark aims for the public sector to use AI to offer world-class services for the benefit of citizens and society. Finland's AuroraAI project aims to use AI to provide personalised, one-stop-shop and human-centric AI-driven public services. Public entities can also use AI to strengthen law enforcement capabilities and to improve policy implementation. AI is also expected to free up public servants' time and allow them to shift to higher value work (Berryhill et al., 2019[4]).

Many countries aim to leverage AI to pursue grand challenges or "moonshot" projects that address high-impact societal challenges. These include climate change, ageing populations, health, inclusiveness, food, energy and environmental security, and other objectives set out in the United Nations' 2030 Agenda for Sustainable Development.

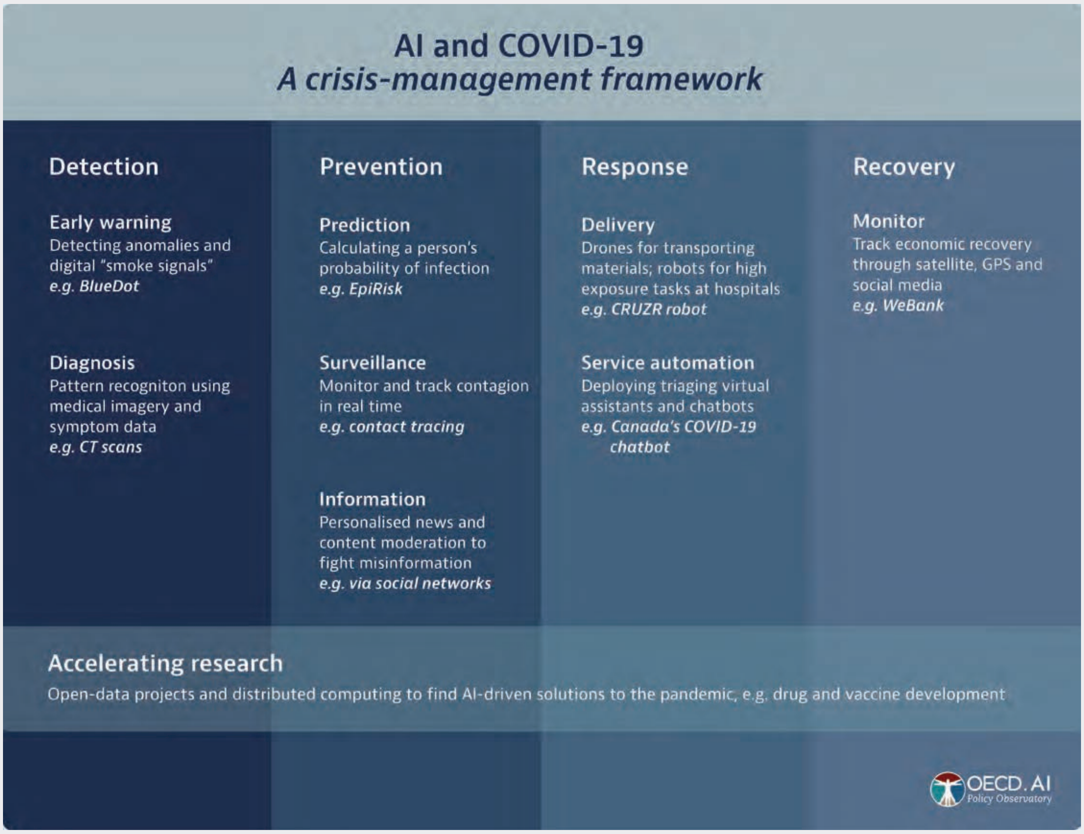
The COVID-19 crisis is generating significant AI R&D. Countries have turned to AI tools to help monitor and predict the spread of the virus in real time and speed diagnosis. They also use AI to gain insights and search for treatments at an unprecedented pace and scale (Box 11.1).

Box 11.1. AI-powered responses to combat COVID-19

Before the world was even aware of the threat posed by COVID-19, AI systems had detected the outbreak of an unknown type of pneumonia in China. AI technologies and tools were employed to support efforts of policy makers, the medical community and society at large to manage every stage of the pandemic crisis management and its aftermath (Figure 11.2):

1. understanding the virus and accelerating medical research on drugs and treatments
2. detecting and diagnosing the virus, and predicting its evolution
3. assisting in preventing or slowing the spread of the virus through surveillance and contact tracing
4. responding to the health crisis through personalised information and learning
5. monitoring the recovery and improving early warning tools.

Figure 11.2. Examples of AI applications at different stages of the COVID-19 crisis



Note: CT = computerised tomography; GPS = global positioning system.

Sources: OECD (2020[5]), *Using Artificial Intelligence to Help Combat COVID-19, https://read.oecd-ilibrary.org/view/?ref=130_130771-3jtyra9uoh&title=Using-artificial-intelligence-to-help-combat-COVID-19*.

Box 11.1. AI-powered responses to combat COVID-19 *(cont.)*

AI tools and techniques helped policy makers and the medical community understand the COVID-19 virus and accelerate research on treatments by rapidly analysing large volumes of research data. AI text and data mining tools were used to help uncover the history, transmission and diagnostics of the virus, as well as management measures and lessons from previous epidemics.

- Deep learning models helped **predict old and new drugs or treatments** to treat COVID-19. DeepMind and others used deep learning to predict the structure of COVID-19 proteins.
- **Dedicated platforms and access to datasets** in epidemiology, bioinformatics and molecular modelling enabled AI experts to contribute to medical research. By October 2020, the COVID-19 Open Research Dataset Challenge by the US government and partners had made over 200 000 research articles on coronavirus available via a dedicated Kaggle platform.
- **Computing power for AI** was made available by technology companies; by individuals donating processing power (e.g. Folding@home); and by public-private efforts such as Microsoft's AI for Health programme and the COVID-19 High Performance Computing Consortium.

Innovative approaches such as hackathons, prizes and open source collaborations helped accelerate research by seeking ideas on using AI to control and manage the pandemic, e.g. in the United Kingdom's CoronaHack – AI vs. COVID-19.

National policies promote the responsible stewardship of trustworthy AI systems

Countries are exploring different approaches to ensure trustworthy AI systems

Alongside promoting wide adoption of AI, national AI strategies focus on policy concerns raised by AI applications. These relate notably to inclusion, human rights, privacy, fairness, transparency and explainability, safety and accountability. With regards to safety, for example, there are concerns about autonomous systems that control unmanned aircraft systems, driverless cars and robots. With regards to fairness, there are concerns about potential bias in AI systems that impact peoples' jobs, loans or health care.

Countries are exploring approaches to ensure trustworthy AI and mitigate risks associated with the development and deployment of AI systems. Initiatives include the development of ethical guidelines and associated voluntary processes, technical standards and codes of conduct, as well as legislative reforms and application-specific regulations.

As in other areas of public policy, regulatory approaches towards AI vary. In January 2020, the United States put forward its goal of having lightweight governmental oversight of AI. This aimed to let AI flourish and avoid unnecessary regulatory burdens on the private sector.

Regulators and policy makers everywhere are paying attention to AI-related issues. For example, the OECD Parliamentary Group on Artificial Intelligence, formed in October 2019, held its first meeting in February 2020. It has a networking and educational (technical and policy) component to help inform national legislative processes.

Many countries have introduced guidelines for trustworthy AI that are largely aligned with the OECD AI Principles and that provide standards for ethical business and good governance. They are addressed to policy makers and regulators, businesses, research institutions and other AI actors. Examples include Australia's AI Ethics Framework, Hungary's AI Ethical Guidelines and Japan's AI R&D Guidelines and AI Utilisation Guidelines. At the European level, the European Commission's independent AI High Level Expert Group (AI HLEG) introduced its Ethical Guidelines on AI in December 2018. In July 2020, the AI HLEG presented its final Assessment List for Trustworthy Artificial Intelligence (European Commission, 2020[6]). In 2019, Singapore's Personal Data Protection Commission released the first edition of a Model AI Governance Framework. It provides guidance to private-sector organisations to address ethical and governance issues when deploying AI solutions (PCPC, 2020[7]).

There are no general mandatory governance instruments specific for AI. However, several governments and intergovernmental bodies are considering or have adopted binding legislation for specific areas of AI technology. For example, Belgium has adopted resolutions to prohibit use of lethal autonomous weapons by local armed forces. Similar application-specific regulations address autonomous vehicles. The Danish ROAD Directorate, for example, has issued a binding guide on driverless cars. In June 2017, Germany allowed drivers to transfer control of vehicles to highly or fully automated driving systems and for those vehicles to be used on public roads. In the United States, the Federal Aviation Administration has been rolling out new regulations, rule-makings and pilot programmes. These aim to speed the integration of unmanned aircraft systems into the national airspace system. In 2020, the US Food and Drug Administration was considering regulation of certain AI-powered medical diagnostic systems (FDA, 2020[8]).

Moreover, certain AI applications deemed to be high risk in terms of their impact on people's lives and liberty are attracting wide regulatory focus across countries. In February 2020, the EC issued a White Paper on Artificial Intelligence – A European Approach to Excellence and Trust. The paper considers requiring a pre-marketing conformity assessment for "high-risk" AI applications such as facial recognition, as a core element of a potential regulatory framework for AI. In addition, the white paper proposes a voluntary "quality label" for AI applications considered not to be high risk (European Commission, 2020[73]). In parallel, the European Commission is reviewing EU product safety and liability regimes in light of AI (European Commission, 2020[10]).

Experimentation allows policy makers to better understand AI impacts

Many countries are considering co-regulatory approaches. These approaches aim to allow experimentation to better understand the effects of AI systems and provide controlled environments to facilitate the scale-up of new business models (see below the section on regulatory sandboxes) (OECD, 2019[11]; Planes-Satorra and Paunov, 2019[12]). These take place in parallel to regulatory approaches to help create a policy environment that can support the transition from research to deployment of trustworthy AI systems.

Standards can help foster interoperable and trustworthy AI systems

Some countries are developing technical standard frameworks to support implementation of the OECD AI principles. Countries including Australia, Canada, China, Germany and the United States emphasise the need for common standards, including to address security issues. For example, the US National Institute of Standards and Technology developed a plan for prioritising federal agency engagement in the development of standards for AI, with public and private-sector involvement. Standards Australia launched Australia's AI Standards Roadmap in March 2020. The roadmap provides a framework for Australians to shape the development of standards for AI internationally. It explores standards that can promote, develop and realise the opportunities of responsible AI, delivering business growth, improving services and protecting consumers (Statistics Canada, 2020[13]).

Several cross-sector (horizontal) and sector-specific (vertical) AI standards are becoming available. Meanwhile, others are being developed by organisations such as the International Organization for Standardization and the Institute of Electrical and Electronics Engineers. Countries, including Denmark, Malta and Sweden, plan to establish AI certification programmes. The Danish government, alongside the Confederation of Danish Industry, the Danish Chamber of Commerce, SMEdenmark and the Danish Consumer Council, has created an independent labelling scheme: the Joint Cybersecurity and Data Ethics Seal. The seal will be granted to companies that meet requirements for cybersecurity and responsible handling of AI-related data (Larsen, 2020[14]).

National policies seek to leverage AI for societies and economies

AI policy initiatives are growing in OECD countries and partner economies. They can be usefully clustered according to the five recommendations to governments for the promotion and development of trustworthy AI in the 2019 OECD AI Principles: facilitating public and private investment in AI R&D; fostering a digital ecosystem for AI; shaping an enabling policy environment for AI; equipping people with the skills necessary to succeed as jobs evolve; and international co-operation for trustworthy AI. However, in a number of cases, AI initiatives address several OECD AI recommendations. In addition, a number of AI policy goals and national policy instruments are aligned with the 2019 OECD AI Principles but not directly addressed in them. These goals relate to AI governance approaches, data governance frameworks, human-machine interaction and AI-related skills migration policies.

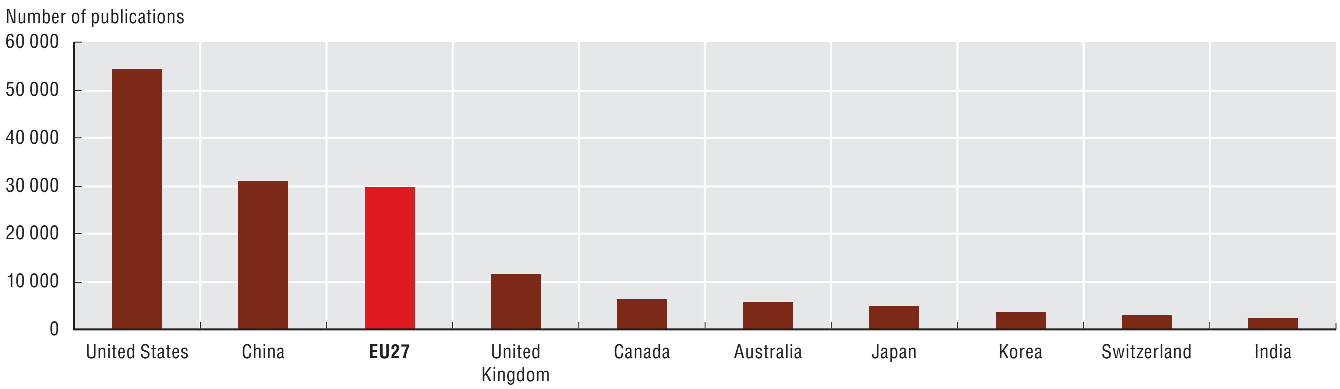
Investment in public research features prominently in AI policies

Enhancing national AI R&D capabilities is a key feature of many national AI policies and strategies. AI is considered to be a general-purpose technology that could impact a large number of industries. It is also called an "invention of a method of invention" (Cockburn, 2018[15]) and already widely used by scientists and inventors to facilitate innovation. Entirely new industries could be created based on the scientific breakthroughs enabled by AI. This underscores the importance of basic research and of considering long time horizons in research policy (Figure 11.3). AI calls for policy makers to reconsider the appropriate level of government involvement in AI research to address societal challenges, especially in promising areas underserved by market-driven investments. In addition, research institutions in all areas will require capable AI systems to remain competitive, particularly in biomedical science and life science fields.

Governments have taken varied action to support AI. They have allocated direct funding for AI research institutes and project grants for AI research projects. They have also established AI centres of excellence to strengthen AI research schemes and create interdisciplinary research communities. Finally, they have launched procurement programmes and innovation vouchers, among others. While there are no official, comparable estimates of public investment in non-defence AI R&D, several budget elements are provided below.

Figure 11.3. AI publications by country, 1980-2020

For top 50% quality rankings, numbers



Notes: EU27 = European Union minus the United Kingdom. Top 50% of AI publications. The "cumulative" option displays aggregate results since 1980. For more information, please see the methodological note at *www.oecd.ai*.

Source: OECD AI Policy Observatory, *www.oecd.ai* (accessed in June 2020).

StatLink https://doi.org/10.1787/888934192851

In North America, Canada's federal and provincial governments have dedicated over CAD 300 million (USD 227 million) to AI research over 2017-22, anchored in the three AI institutes of the Pan-Canadian AI Strategy. The United States' AI R&D budget for the fiscal year (FY) 2021 plans a significant increase in non-defence AI funding over the FY2020 budget of USD 1 billion (NCO et al., 2019[16]). It includes over USD 850 million for AI activities funded by the National Science Foundation (NSF), an increase of more than 70% over the FY2020 budget. The NSF will invest in both foundational and translational AI research and plans to create national AI research institutes in collaboration with the departments of Agriculture, Homeland Security, Transportation and Veterans Affairs. The objective is to convene multisector, multidisciplinary research and workforce efforts. The US FY2021 budget also includes an increase of USD 54 million in core AI research at the Department of Energy. Finally, the National Institutes of Health is investing an additional USD 50 million for new research on using AI to help tackle chronic diseases (United States, 2020[17]).

In China, the State Council released the Guideline on Next Generation AI Development Plan in 2017. This aims to achieve: i) AI-driven economic growth in China by 2020; ii) major breakthroughs in basic theories by 2025 and in building an intelligent society; and iii) for China to be a global AI innovation centre by 2030 and to build up an AI industry of CNY1 trillion (USD 150 billion) (China, 2017[18]). Data on Chinese public investment in AI R&D are not readily available. However, researchers at Georgetown's Centre for Security and Emerging Technology estimated that public AI R&D in 2018 was comparable to the planned spending of the United States for FY2020. They also put forward that Chinese public AI R&D spending likely focuses on applied research and experimental development rather than basic research (Acharya and Arnold, 2019[19]).

The European Commission, which has committed EUR 1.5 billion to AI research over two years as part of its Horizon 2020 programme, launched a new call for research into COVID-19. This contributes to its EUR 1.4 billion pledge to the Coronavirus Global Response initiative, launched by President Ursula von der Leyen on 4 May 2020. The European Union expects the private sector and its member states at the national level to complement this investment, reaching at least EUR 20 billion invested by the end of 2020. It also expected the private sector and member states to continue investing at least EUR 20 billion annually for the next ten years in AI R&D. Funding through Horizon Europe and the new Digital Europe programme targets AI research, innovation and deployment, and the development of digital skills. Support for AI R&D also includes grants to establish centres of excellence. This includes EUR 20 million to build the European Network of AI Excellence Centres (AI4EU), a European online platform that allows the exchange of AI tools and resources.

At the European national level, Germany had set aside EUR 3 billion for 2019-25 for the implementation of its national AI strategy. Germany expects a leverage effect on business, science and the *Länder* (states) that will at least double the overall amount available. The French AI strategy dedicates EUR 700 million for public AI research over five years from 2021-22. This amount is part of the EUR 1.5 billion for development of AI, notably in AI research institutes in Grenoble, Nice, Paris and Toulouse. In the 2019 State Budget, the Danish government allocated DKK 215 million (EUR 27 million) to the Innovation Fund Denmark to research technological possibilities offered by AI. The Finnish Centre for AI, a nationwide competence centre for AI with Academy of Finland flagship status, has been allocated EUR 250 million funding for the next eight years. Singapore will invest up to USD 150 million over five years in "AI Singapore".

AI uptake requires accessible data, technologies and infrastructure

Data access and sharing are key to accelerate AI uptake

Many countries continue to focus on providing access to public sector data, including open government data, geo-data (e.g. maps) and transportation data. Similarly, they also emphasise data sharing within the public sector (Chapter 5). Countries are building on their open data access policies and strategies to promote data access and sharing for AI. For example, Denmark plans to provide open access to weather, climate and marine data from the Danish Meteorological Institute, in addition to European co-operation on space data. The United Kingdom is making available high-quality public data in an open, reusable and accessible format for machine learning. The United Kingdom's Geospatial Commission aims to improve access to geospatial data, including for AI uses. In light of the United States' Executive Order on Maintaining American Leadership in AI, the Office of Management and Budget is consulting the public on needs for additional access to, or improvements in the quality of, federal data and models that would improve AI R&D and testing efforts.

Several national AI policies plan to develop centralised, accessible repositories of open public data. In Norway, the Brønnøysund Register Centre and the Norwegian Digitalisation Agency have established a national directory of data held by different public agencies, their relationships, what they mean and whether data can be shared and on what terms. Portugal also plans to create a centralised repository for administrative data.

Organisations focused on data have also been created or are being considered. The Spanish AI strategy, for example, recommends the creation of a National Data Institute. Countries and regional institutions also seek to incentivise data sharing in the private sector. The United Kingdom in collaboration with the Open Data Institute and Innovate UK has launched three pilot projects to explore data trust frameworks for safe, secure and equitable data transfer. The European Union is creating a European data space, which will include private and public data. In February 2020, the European Union launched the EU data strategy together with the White Paper on AI as the first pillar of the European Commission's new digital strategy (European Commission, 2020[20]).

Uptake also requires AI technologies and infrastructure

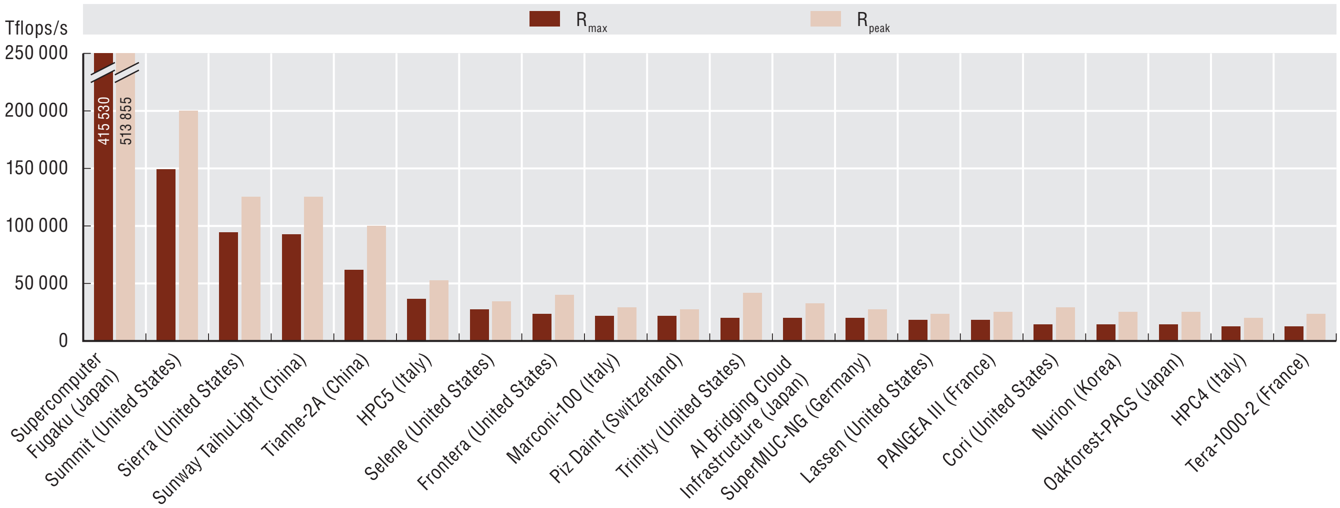
Developing and using AI requires access to AI technologies and infrastructure. This supposes affordable high-speed broadband networks and services, computing power and data storage, as well as supporting data-generating technologies such as the Internet of Things (IoT). In terms of network infrastructure, many countries are setting up high-quality connectivity and have or plan to deploy nationwide 5G technology and 5G networks (Chapter 3). The United Kingdom's AI strategy mentions public investment of GBP 1 billion (USD 1.24 billion) to boost digital infrastructure, including GPB 176 million (USD 219 million) for 5G and GBP 200 million (USD 249 million) for full-fibre networks.

Many software tools to manage and use AI exist as open source resources, which facilitates their adoption and allows for crowdsourcing solutions to software bugs. Tools include TensorFlow (Google) and Cognitive Toolkit (Microsoft). Some researchers and companies share curated training datasets and training tools publicly to help diffuse AI technology.

Algorithms and data play strong roles in the development and performance of AI systems. However, as AI projects move from concept to commercial application, they often need specialised and expensive cloud computing and graphic-processing unit resources. Several economies allocate high-performance and cloud computing resources to AI-related applications and R&D (United States, 2019[21]). Some are setting up supercomputers designed for AI use and devoted to research and/or providing financial support to develop the national high-performance computing infrastructure (Figure 11.4).

The European High-Performance Computing Joint Undertaking (EuroHPC) is a EUR 1 billion undertaking by the European Union and other European countries. They aim to develop a peta-scale and pre-exa-scale supercomputing and data infrastructure to support European scientific and industrial research and innovation. In Japan, the RIKEN Center for Computational Science in Kobe and Fujitsu are developing a supercomputer named Fugaku. In addition to its Summit scientific supercomputer launched in June 2018, the US Department of Energy is building the Frontier supercomputer, expected to debut in 2021 as the world's most powerful high-performance computer for AI. The NSF also invests significantly in next-generation supercomputers for AI R&D such as Frontera. The National Aeronautics and Space Administration also has a strong high-end computing program. Moreover, it is augmenting its Pleiades supercomputer with new nodes specifically designed for MLAI workloads (United States, 2019[21]).

Figure 11.4. The 500 most powerful non-distributed computer systems, by location, July 2020



Notes: This figure clusters the 500 most powerful non-distributed computer systems based on data from TOP500 from July 2020. A system's R_{max} score describes its maximal achieved performance. A system's R_{peak} score describes its theoretical peak performance. Tflop/s is a rate of execution, i.e. of trillions of floating point operations per second. StatLink contains more data.

Source: OECD based on TOP500, *www.top500.org/lists/top500/2020/06/* (accessed on 10 September 2020).

StatLink https://doi.org/10.1787/888934192870

AI needs an enabling policy environment to generate benefits

Countries seek to support an agile transition from R&D to real use of AI in four ways. First, they provide controlled environments for experimentation and testing of AI systems. Second, they seek to improve access of companies to funding, including SMEs and start-ups. Third, they connect emerging companies with business opportunities. Fourth, they provide tailored advisory to support their scale-up.

These controlled environments for AI experimentation and testing facilitate the timely identification of potential technical flaws and governance challenges. In so doing, they can reveal potential public concerns through testing under quasi real-world conditions (OECD, 2017[9]). Such environments include innovation centres, policy labs and regulatory sandboxes. The latter are a form of limited regulatory testing for innovative applications not intended to enable permanent regulatory waivers or exemptions (OECD, 2020[22]). Experiments can operate in "start-up mode" whereby they are deployed, evaluated and modified, and then scaled up or down, or abandoned quickly (OECD, 2020[22]). Co-creation governance models involving both governments and private stakeholders already play an important role in many national AI strategies, such as those of Germany, New Zealand, Korea, the United Kingdom and the United States.

Germany's AI strategy plans the establishment of AI living labs and testbeds, such as the living lab on the A9 autobahn. These make it possible to test technologies in a real-life setting and to screen the regulatory environment and make adjustments (Federal Government of Germany, 2018[23]). Lithuania plans to create a regulatory sandbox that will allow the use and testing of AI systems in the public sector. The United Arab Emirates launched an AI Lab in 2017. Led by Smart Dubai, the lab is testing use cases across all types of city services – from police and security to land development, education and environment. The European Commission is considering development of large-scale AI testing and experimentation facilities, which will be available to all actors across Europe to help avoid duplication of efforts. These testing facilities may include regulatory sandboxes in selected areas (European Commission, 2020[24]).

To spur private-sector investment in AI projects, some countries have created financial incentives. Since January 2018, the United Kingdom has provided an AI R&D Expenditure Credit (12% tax credit) designed to stimulate uptake of AI, including within the public sector. Malta has also reformed the Seed Investments Scheme with more favourable tax credit conditions for innovative AI firms. In Italy, the Ministry for Economic Development has provided funding for Telecom Italia to scale up several AI solutions, including in the areas of conversational virtual assistants and anomaly detection for alarm systems and predictive maintenance.

Another way that countries boost the development of innovative AI research ecosystems is by establishing networking and collaborative platforms, such as AI hubs, AI labs and AI accelerator programmes. They facilitate co-operation between industry, academia and public research institutes. Canada's Innovation Superclusters Initiative invites industry-led consortia to invest in regional innovation ecosystems. It also supports partnerships between large firms, SMEs and industry-relevant research institutions. Denmark's national AI strategy plans a Digital Hub for public-private partnerships.

Finland's AI Business programme encourages new AI business ecosystems and investments in Finland. In Hungary, the AI in practice self-service online platform allows developers to showcase technologies and local case studies to foster collaboration and awareness. The United Arab Emirates' Dubai AI lab – a partnership between different parts of government, IBM and other partners – provides essential tools and go-to-market support to implement AI services and applications in different areas. Portugal has established Digital Innovation Hubs on production technologies, manufacturing and agriculture, as well as collaborative laboratories (CoLabs) (Portugal, 2019[25]). The Czech Republic is developing specific support grants and investment programmes for SMEs, start-ups and spinoffs with innovative services and business models.

Countries are introducing a wide range of policy measures and initiatives to spur innovation and AI adoption by SMEs (OECD, forthcoming[26]). The European Commission's AI4EU project is an AI-on-demand platform to help EU SMEs adopt AI. Canada has invested CAD 950 million (EUR 608 million) in five regional Innovation Superclusters, one of which focuses on accelerating the application of AI for supply chains (SCALE.AI). Finland's AI Accelerator, initiated by the Ministry of Economy and Employment with Technology Industries of Finland, spurs AI use in SMEs. In the United Arab Emirates, Dubai Future

Accelerators facilitates collaboration between government entities, private-sector organisations and start-ups, scale-ups and innovative SMEs to co-create solutions to global challenges. Korea's AI Open Innovation Hub provides SMEs and start-ups with data, algorithms and high-performance computing resources to allow them to innovate with AI. Germany's AI strategy includes support for SMEs and start-ups through regional AI clusters that foster science-industry collaboration and AI trainers in Mittelstand ("SME") 4.0 Centres of Excellence.

As AI changes jobs and societies, people require new skills

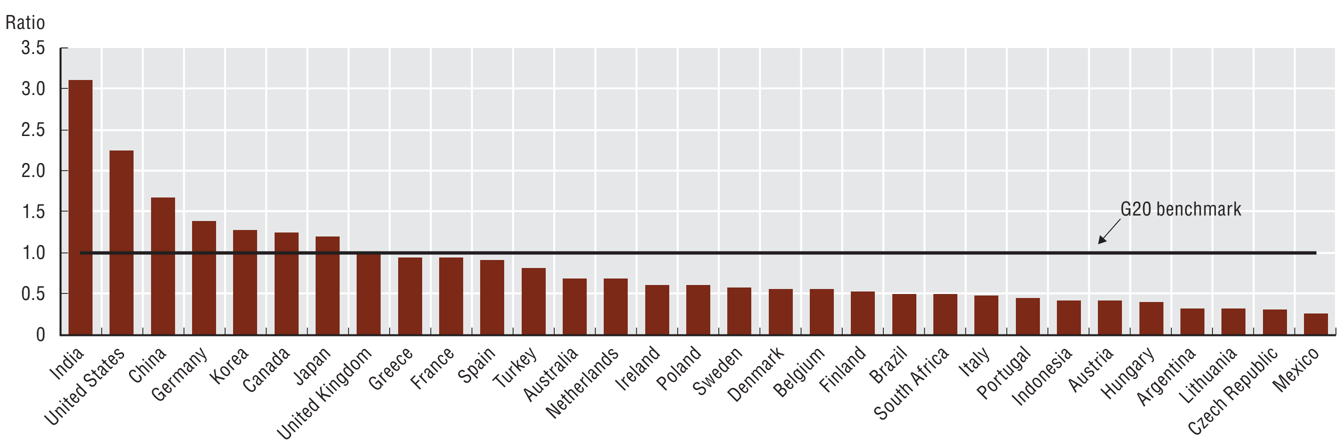
Automation is not a new phenomenon, but AI is expected to change, and perhaps accelerate, the profile of tasks that can be automated. Many countries are conducting research to understand the impacts of AI in a range of workplace settings. For example, the United States' NSF awarded grants under The Future of Work at the Human-Technology Frontier, a "big idea" programme. The funded projects aim at understanding the impacts of AI in different workplace settings.

National institutions are closely monitoring the impact of AI on the labour market. France created a Centre of Excellence for AI to help recruit AI talent and to serve as an advisor and lab for public policy design. With the establishment of its AI Observatory, Germany plans to systematically monitor and analyse the implications of smart and autonomous systems in the world of work. The Czech Republic will monitor the impact of technological changes on the labour market. Poland also plans to create an AI Observatory for the Labour Market.

As AI systems take over some tasks long performed by humans, new opportunities will emerge in the workplace. However, AI will also bring new challenges with transitions in the labour market and disruption to livelihoods. Governments are adapting existing policies and developing new strategies to prepare citizens, educators and businesses for the jobs of the future and to minimise the negative impacts. Many national AI policies emphasise retraining for those displaced by AI, and education and training for workers coming into the labour force.

Countries have identified AI talent as the bedrock of technological advancement in AI, and education and skills are a priority for all national AI strategies. One focus is on increasing the penetration of AI skills at the national level (Figure 11.5). This would be accomplished through formal education and training programmes on AI, including education in science, technology, engineering and math (STEM); training in IT and AI tools and methods; and domain-specific education (Vincent-Lancrin and van der Vlies, 2020[27]). The American AI strategy emphasises STEM education as a key priority. It devotes at least USD 200 million in grant funds per year to promote high-quality computer science and STEM education, including the training of teachers. Finland plans to create new AI Bachelor's and Master's programmes and courses on AI and to promote incentives and training mechanisms for teachers to use AI in their courses and teaching methods.

Figure 11.5. Cross-country AI skills penetration, 2015-19



Notes: Average from 2015 to 2019 for a selection of countries with 100 000 LinkedIn members or more. The value represents the ratio between a country's AI skill penetrations and the benchmark, controlling for occupations. For more information, please see the methodological note at *www.oecd.ai*.

Source: OECD AI Policy Observatory, *www.oecd.ai* (accessed in April 2020).

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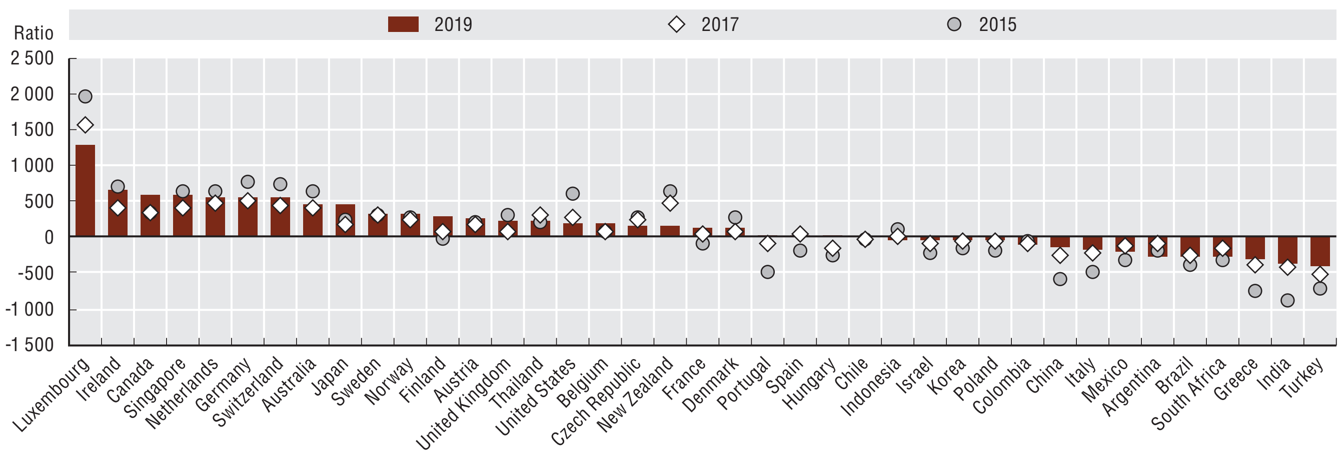
Moreover, many countries are offering fellowships, postgraduate loans and scholarships to increase domestic AI research and expertise. Australia has dedicated AUD 1.4 million (USD 0.89 million) to AI and Machine Learning PhD scholarships. The United Kingdom plans to create 16 centres for doctoral training at universities across the country to deliver 1 000 new PhDs over the next five years. Singapore aims to enhance its AI capabilities by bringing together Singapore-based research institutions and AI start-ups and companies to grow knowledge, create tools and develop AI talent domestically.

There are concerns about the shortage of skilled AI workers and the migration of researchers and engineers to other countries (Figure 11.6). Many national AI strategies also include incentives to retain and attract foreign skills and top talent in AI. Belgium plans to attract world-class data and AI talent by introducing migration quotas to facilitate selective immigration and visa policies for top foreign talent. The United Kingdom plans to increase the amount of Exceptional Talent (Tier 1) visas (up to 2 000 per year) to attract science, technology and AI specialists. It has established Turing Fellowships to attract and retain top AI researchers.

Figure 11.6. Between-country AI skills migration, 2019

Net skill migration ratio



Note: Net skill migration ratio is calculated by dividing net skill flows to a given country by the existing skill stock. Net flows are defined as total arrivals minus departures within the given time period. LinkedIn membership varies considerably between countries, which makes difficult the interpretation of absolute movements from one country to another. To compare migration flows between countries fairly, migration flows are normalised for the country of interest. For example, if country A is the country of interest, all absolute net flows into and out of country A, regardless of origin and destination countries, are normalised based on LinkedIn membership in country A at the end of each year and multiplied by 10 000. Hence, this metric indicates relative talent migration from all countries to and from country A. StatLink contains more data.

Source: OECD AI Policy Observatory, *www.oecd.ai* (accessed in April 2020).

StatLink https://doi.org/10.1787/888934192908

Countries are also devising vocational training and lifelong learning programmes. These aim to help their citizens keep up with technological and societal changes over the long term. This, in turn, ensures the public can make use of IT-enabled resources and that the domestic workforce is available and qualified for the jobs of the future. Finland's Elements of AI programme is a ten-hour Massive Open Online Course that seeks to ensure that all citizens have a basic understanding of AI. Finland's AI strategy is interesting because it sets out to educate the country's entire population – including people who are employed and the elderly – in basic AI, which it sees as a "civic competence". While Finland initially targeted the training of 1% of its population, the course attracted more than 100 000 participants. This represents more than 2% of the population.

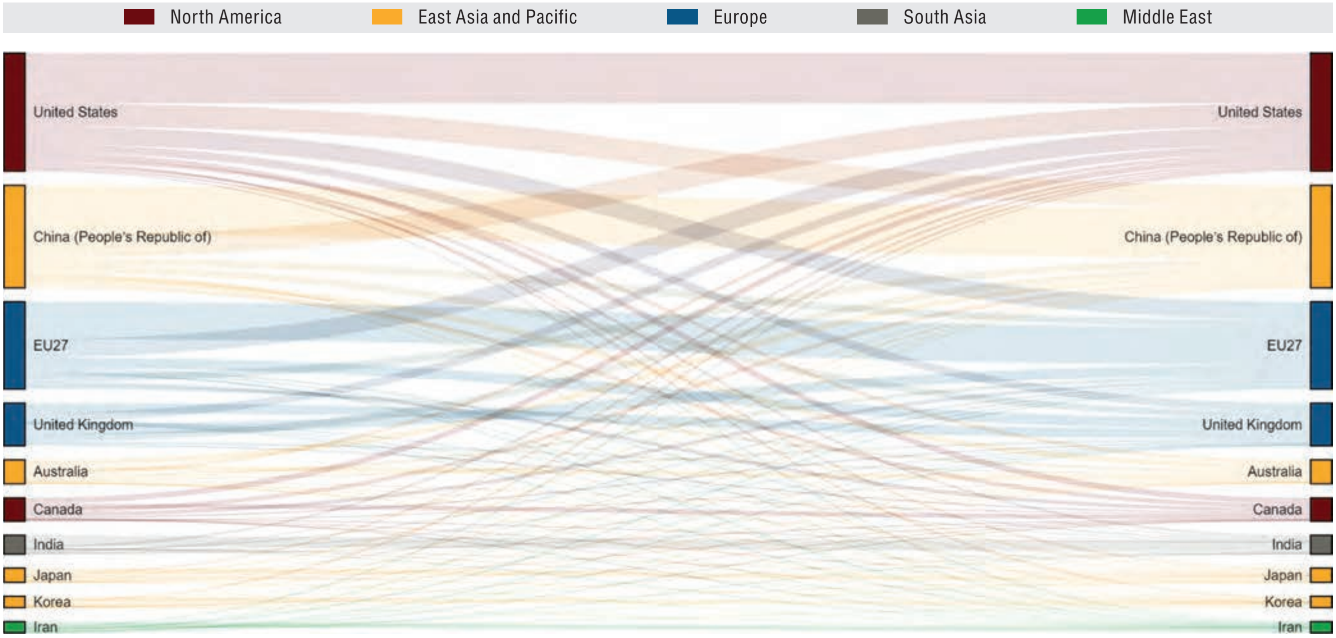
At the same time, AI can help governments match labour supply and demand. For example, Korea's AI service – The Work – helped 2 666 job seekers find relevant offers that led to a job in the second quarter of 2019. Korea has since put in place a pilot service using a chatbot named Goyong-yi ("employment") to provide 24/7 automated customer support.

In parallel, national AI strategies support a persistent and robust AI education ecosystem. To that end, they co-ordinate and collaborate among the government and with the business, educational and non-profit communities in developing educational programmes, tools and technologies. Korea's Smart Training Education Platform will allow people to take training programmes that combine theory and field experience. Through its learning platform on artificial intelligence (KI-Campus) Germany's Federal Ministry of Education and Research brings together expertise from science, industry and society. It is a forum for exchange and co-operation on technological, economic and societal challenges regarding the research and application of AI.

International co-operation initiatives are proliferating

Cross-border research on AI is significant (Figure 11.7). For example, the French National Research Agency, the German Research Foundation and the Japan Science and Technology Agency have called for trilateral French-German-Japanese collaborative research on AI over three years. Many EU countries are also participating in European AI research projects and networks such as BVDA/EURobotics, the Confederation of Laboratories for Artificial Intelligence Research in Europe (CLAIRE) and the European Laboratory for Learning and Intelligent Systems (ELLIS). AI is also a priority in Horizon Europe, the European Union's next framework programme for research and innovation.

Figure 11.7. Domestic and international AI research collaboration, 1980-2020



Notes: EU27 = the European Union minus the United Kingdom. The thickness of a connection represents the number of joint AI publications between two countries since 1980. "Domestic collaboration" shows co-authorship involving different institutions within the same country. For more information, please see the methodological note at *www.oecd.ai*. StatLink contains more data.

Source: OECD AI Policy Observatory, *www.oecd.ai* (accessed in July 2020).

StatLink *https://doi.org/10.1787/888934192927*

There are numerous international co-operation initiatives at the regional level. For example, the Arab AI Working Group, formed in 2019 by the Arab League members, has four goals. First, it aims to develop a joint framework for capacity building in the Arab region. Second, it raises awareness of the opportunities and challenges of AI. Third, it trains youth to compete in AI jobs. Finally, it works to establish a common Arab Strategy, which includes a regulatory framework for AI and guidance on using AI to serve the goals of Arab countries. Meanwhile, under Egypt's presidency in 2020, the African Union set up a working group on AI. The working group plans to create a joint capacity-building framework across the continent. This will address skills gaps and prepare African youth for future jobs; identify and initiate AI projects across Africa to serve the Sustainable Development Goals (SDGs); and establish a common AI strategy for Africa.

International co-operation for AI is also taking place in fora including the OECD, the Group of Seven (G7), the Group of Twenty (G20), the European Union, the Council of Europe and the United Nations Educational Scientific and Cultural Organization (UNESCO).

- OECD countries adopted the OECD AI Principles in May 2019, the first set of intergovernmental principles and recommendations to governments for trustworthy AI. In July 2019, the OECD's Committee on Digital Economy Policy agreed to form a multidisciplinary and multi-stakeholder OECD Network of Experts on AI (ONE AI) to develop practical guidance for implementing the OECD AI Principles for trustworthy AI. In February 2020, the OECD launched the OECD AI Policy Observatory (OECD.AI),[2] a platform to share and shape AI policies (OECD, 2020[28]) that provides data and multidisciplinary analysis on artificial intelligence.
- The Global Partnership on AI (GPAI) is a voluntary multi-stakeholder effort launched in June 2020 to promote responsible AI use that respects human rights and democratic values. The Partnership was conceived by Canada and France during their G7 presidencies and at its launch counted 13 other founding members: Australia, the European Union, Germany, India, Italy, Japan, Korea, Mexico, New Zealand, Singapore, Slovenia, the United Kingdom and the United States. The GPAI brings together experts from industry, government, civil society and academia, to advance to advance cutting-edge research and pilot projects on AI priorities.
- In 2020, the Saudi G20 presidency steered the G20's AI work towards a policy of Realizing Opportunities of the 21st Century for All (G20, 2019[29]). This work built on the legacy of the Japanese 2019 presidency under which the G20 adopted human-centred AI principles that draw from the OECD AI Principles. AI was part of the 2020 discussions under the G20 Digital Economy Task Force, as well as during an Extraordinary G20 Digital Economy Ministerial Meeting. This latter meeting recognised AI as having potential to contribute to the fight against pandemics (G20, 2020[30]).
- In September 2019, the Committee of Ministers of the Council of Europe (CoE) set up the Ad Hoc Committee on Artificial Intelligence. This committee was examining the feasibility of developing a legal framework for the development, design and application of AI, based on CoE standards on human rights, democracy and rule of law. In April 2020, the same Committee of Ministers issued a set of guidelines calling on governments to take a precautionary approach to development and use of algorithmic systems. It further called for adoption of legislation, policies and practices that fully respect human rights (Council of Europe, 2020[31]).
- In his Roadmap for Digital Cooperation, the United Nations Secretary General called for the establishment of a multi-stakeholder advisory body on global AI co-operation. The body will provide guidance on artificial intelligence that is trustworthy, human rights-based, safe, sustainable, and promotes peace, by bringing together a diverse group of relevant entities in the AI landscape to address issues around inclusion, co-ordination, capacity-building, sharing and promoting best practices, as well as exchanging views on artificial intelligence standardisation and compliance efforts.
- Many other UN institutions are also engaged in initiatives to address AI challenges (ITU, 2019[32]). UNESCO launched a global dialogue on the ethics of AI due to its complexity and impact on society and humanity. In November 2019, UNESCO's 40th General Conference mandated the organisation to develop a recommendation on the ethics of AI, which will be considered for adoption in November 2021 (UNESCO, 2020[33]).

Blockchain and other distributed ledger technologies

Blockchain, and other distributed ledger technologies (DLTs[3]), offer an alternative way of securing data and transaction records for use by multiple parties without reliance on a trusted, central authority. DLTs allow an immediate and secure digital transfer of value and ownership within a network, in total transparency. Consequently, they could profoundly reshape economic transactions. The technology has all the characteristics of a general-purpose technology, which means it is pervasive, improvable over time and allows complementary innovations (Box 11.2).

DLTs have growing implications. Initially, DLTs emerged as the technology behind cryptocurrencies such as Bitcoin and Ether. Today, DLTs are changing business models and offering new ways to exchange value and trace its creation, with impacts across a wide range of policy areas.

Box 11.2. Key features of blockchain

Distributed. In a blockchain, each node independently constructs its own record of transactions. This means, at all times, each node maintains copies of the same ledger. As such, the record is highly secure since, to change the ledger, each version held by the different nodes would need to be changed. In other words, a malicious actor would need to attack all, or at least a majority, of the nodes rather than just one single, centralised record-keeper. In other systems, different parties to a transaction would maintain multiple different records, which would then need to be cross-checked for verification. With blockchain, the ledgers automatically synchronise through a consensus mechanism.

Immutable. Given its use of cryptography, once a transaction is added to blockchain it generally cannot be undone. As such, all users can have confidence in the transaction. Unlike in a centralised database, the record cannot be altered, whether through error or misfeasance.

Source: OECD (2019)[34], "Blockchain at the OECD", *https://www.oecd.org/going-digital/blockchain-at-the-oecd.pdf.*

The promise of blockchain adoption brings policy challenges

Asset tokenisation disrupts the financial markets in multiple ways

Despite reaching a peak in the technology "hype cycle", DLT is still in its infancy in terms of both development and adoption (OECD, 2019)[34]. The pace of change is rapid, however. Further, some applications, particularly DLT-based digital financial assets (Box 11.3) already in use. Consequently, policy makers require a clear understanding of the technology and the challenges arising from its adoption (OECD, 2020[22]).

Box 11.3. Digital financial assets

Tokenisation describes the process of transferring rights to a physical or digital asset into a digital representation – or token – on a blockchain. Being in possession of that digital token provides the right to that asset, and the ability to trade and track it digitally. In addition to tokenisation of physical assets, there are three main types of DLT-based digital financial assets:

1. **Payment tokens**. Intended to operate like traditional, fiat currencies (legal tender backed by the issuing government), payment tokens are usable as a means of exchange for any goods or services, and possibly also as a store of value. Bitcoin is the most well-known example.
2. **Security (or asset and financial) tokens**. These are designed as tradeable assets held for investment purposes and classified as a security (or equivalent) under applicable laws. BCAP tokens issued by Blockchain Capital are an example. Through investments in the fund, token holders gain exposure to the venture capital market.
3. **Utility (or consumer) tokens**. Their primary use is to facilitate exchange of, or access to, specific goods or services. They may act as a licence to allow the holder access to a particular service. They can function as a pre-payment or voucher for a good or service (and may be issued even before the relevant good or service is available). Storj, for example, provides access to a peer-to-peer network cloud storage service. Meanwhile, the Brave search engine uses the Basic Attention Token to reward users for their search data.

Source: OECD (2019)[34], "Blockchain at the OECD", *https://www.oecd.org/going-digital/blockchain-at-the-oecd.pdf.*

In terms of trading implications, disintermediation enabled by DLTs may affect the traditional market-making function as it removes the need for dealer intermediation. Buyers and sellers in a decentralised market for "tokens" (i.e. a digital representation of the rights to an asset) are matched automatically. The growth of asset tokenisation activity could also have an impact on the repurchasing (repo) activity for the funding of positions. In addition, it could affect securities lending activities used as part of trading strategies. The shift of the above activities on to a DLT-based system has the potential for faster and less costly securities lending. Fewer steps are involved in the process and transfer/unwinding of collateral is direct and instantaneous.

Any asset can theoretically be tokenised. Therefore, the number and diversity of assets that would trade in public markets and gain liquidity could increase as per the liquidity implications in a scenario of proliferation of asset tokenisation.

Furthermore, trading in a tokenised environment can benefit from the enhanced transparency provided in DLT-based networks. An advantage of improved transparency is fewer information asymmetries, which could improve the price discovery mechanism. This, in turn, would provide investors with incentives to increase their participation and bring additional liquidity in the market. It would also improve competition conditions in the market.

Traditional post-trade processes have three inefficiencies. First, both sides of the trade need to maintain records of the information around the transaction. Second, the need to maintain this information generates counterparty risks. Finally, it costs money to reconcile each party's data with the data of the counterparty at each step of the contract execution (Mainelli and Milne, 2016[35]).

The use of blockchain in post-trade addresses these inefficiencies. It allows for the maintenance of a single, shared, immutable ledger of transaction information. This ledger is updated at each step of the process and can be instantly accessed by all involved parties. DLT-enabled systems and the use of smart contracts for clearing and settlement of tokenised assets can verify ownership, confirm trade matching and record transactions in an automated, immutable, transparent and near-immediate way. Therefore, the distributed ledger can act as a decentralised registry of data on transactions, and a counterparty to all transacting parties.

From a policy perspective, tokenised markets should comply with regulatory requirements that promote financial consumer and investor protection, market integrity and competition, and seek to guard against build-up of systemic risks (OECD, 2020[22]). Tokenised assets can be seen as cryptography-enabled, dematerialised securities based on DLT-enabled networks. Instead of electronic book-entries in securities registries of central securities depositories, DLT-enabled networks merely replace one digital technology with another. Therefore, they do not raise issues in jurisdictions with a technology-neutral approach to regulation. Nevertheless, it can sometimes be difficult to be certain whether tokenisation falls within or is fully captured by the regulatory perimeter. This is especially true given the novel nature of some new business models and processes involved in tokenised markets.

The full implications of tokenised assets, tokenisation processes, the markets in which they trade and the processes involved are not understood. For example, it is not clear if they fully comply with the regulatory and supervisory framework covering the corresponding asset markets, particularly for digitally native assets. Given the inherent global nature of decentralised networks enabled by DLTs, such gaps would need to be examined both on a national and cross-jurisdictional basis. In addition, the absence of a central point of accountability due to the decentralised nature of the network may impede regulatory action when such mechanisms are used.

At the same time, market participants may not fully understand tokenised assets that fall within the legal and regulatory perimeters of policy frameworks and regulatory regimes. Regulatory or legal ambiguity around asset tokenisation can create uncertainties and risks for participants in tokenisation markets. This can undermine the smooth functioning of such marketplaces. Further, it could have potential indirect impact on the conventional, off-chain markets (traditional assets and financial management institutes) for such assets. Legal and regulatory ambiguity also slow down the adoption rate of such technologies. Individuals are uncertain of the conditions under which they can participate in such markets and/or engage investors.

Greater clarity around the regulatory and supervisory frameworks applied to tokenised assets and markets is a stepping stone to their safe development and use. Existing regulation may need to apply to new actors. For example, a trusted third party could guarantee the accuracy of information at the onboarding of the asset on to the DLT system ("on-chain") and safeguard the asset. In addition, new requirements may be needed. These might cover interoperability between DLTs, or the interaction or gateways linking the on-chain and off-chain environments. New risks may arise for the application of DLT technologies related to operations or digital identities. These will need to be appropriately supervised. Different institutions regulate and supervise virtual assets at the national level. They need a co-ordinated approach to cover all facets of such activity. These range from payments, investments, taxes and accounting to compliance with anti-money laundering and combating the financing of terrorism policies, law enforcement and other crime prevention (OECD, 2020[22]).

Other policy implications of tokenised assets relate to international co-operation to limit regulatory arbitrage. They also relate to the smooth operation of cross-border transactions, financial consumer protection, market integrity and financial education for the protection of investors in tokenised markets.

Access to finance for SMEs

DLTs bring new alternatives for SMEs to access finance. SMEs are the backbone of most economies, accounting for nearly 99% of all firms in OECD countries. Young innovative firms are crucial for economic growth and job creation. This is especially the case during post-crisis recovery periods such as the one that will follow the COVID-19 pandemic. However, SMEs often lack collateral or a business track record so they can encounter obstacles when seeking finance. Not all start-ups require (or deserve) external capital. However, they often encounter difficulties in obtaining seed and early stage financing because of uncertain profit expectations and riskier growth perspectives.

The use of initial coin offerings (ICOs) for financing SMEs gained interest recently. An ICO is the cryptocurrency industry's equivalent to an initial public offering. A company looking to raise money to create a new coin, app or service launches an ICO. Interested investors can buy into the offering and receive a new cryptocurrency token issued by the company. This token may have some value in using the company's product or service, or it may just represent a stake in the company or project.

ICOs facilitate the exchange of value without the need for a trusted central authority or intermediary (government, bank), which enhances efficiency. The disintermediation that occurs in ICOs could "democratise" SME financing, distributing control among SMEs and participants/token-holders. This would be in contrast to concentrating decision power in the hands of financiers, as is the case with banks in traditional debt financing. At the same time, SMEs diversify their financing options. This allows them to base their appeal on both profit potential and other characteristics of their project. This, in turn, could encourage banks to seek alternative ways to determine their SME financing methods (OECD, 2019[36]).

ICOs offer an innovative way to raise capital for young and innovative SMEs, enabled by DLTs. Under specific caveats, regulated forms of ICOs could become an alternative financing mechanism for young SMEs with DLT-related projects. On the one hand, they could improve competition in the SME financing space. On the other, they could facilitate faster financing of SMEs at a lower cost compared to most traditional financing mechanisms. In this way, they would benefit from cost efficiencies derived from automation and disintermediation through the use of DLTs and the blockchain.

The ICO "hype" in the second half of 2017 and first half of 2018 was followed by a decline. This opened the field for security token offering (STOs); simple agreements for future tokens (SAFTs) that refer to agreements for the future transfer of tokens from cryptocurrency developers to investors; and normal equity rounds (Bianchini and Kwon, 2020[37]).

Various factors contribute to the increasingly scarce use of this instrument. Many projects were not able to deliver on the promises of their white paper. The technology was still not at the necessary level of maturity. At the same time, regulations caught up, clarifying the necessary compliance for different type of tokens and initiatives. Institutional investors may not have opened large positions in the crypto-assets space.

Stakeholders such as venture capitalist and hedge funds have started using different means to secure early access to promising blockchain projects. SAFTs, for example, ensure conversion of the investors' assets in tokens once the company issues them. Another example are STOs, a regulated version of ICOs in which the issue of tokens is considered a security event that falls under traditional security regulations and taxation rules.

Together with usual equity rounds, financing of innovative start-ups in the blockchain space is going back to the more traditional start-ups investment patterns. In this scenario, early access is open only to professional investors. This calls for particular attention by policy makers.

Traceability in supply chains

Blockchain applications are also garnering wide interest beyond the financial sector. The properties of decentralisation and immutability of data stored on the blockchain make the technology suitable for use in industrial processes where transparency and traceability is crucial. For example, a number of blockchain platforms are being developed to facilitate supply-chain tracing of products ranging from diamonds to cheese. Detailed information of products are stored on blockchain throughout their journey, while leveraging complementary technologies such as the IoT. Data stored on the blockchain typically refer to sourcing and treatment of material, as well as logistics. Such systems enable businesses to see their supply chain better, and also provide more transparency to the end-consumers on the products they choose. The use of blockchain also makes it easier to verify authenticity of the products through the scanning of QR code or radio frequency identification. This, in turn, helps fight counterfeiting and violations of intellectual property. The verification function of blockchain could also promote sustainability, where the information regarding products' compliance to labour or environmental standards within supply chains can be verified.

Better integrated transport services

As in several sectors of the economy, digital transformation continues to reshape the transport industry, supporting a system based on deeper co-ordination of urban mobility services. DLTs have the potential to support broader co-ordination of seamless urban mobility services and the delivery of Mobility as a Service (MaaS) in urban settings (ITF, 2018[38]). Like other sectors, transport could be profoundly transformed by blockchain, and other novel DLTs that allow decentralised applications to run in peer-to-peer networks. These technologies allow agents to enter into direct relationships with each other. Agents adhere to a common set of rules and a high degree of trust without passing through a central authority. Combining a common language and syntax for the "Internet of mobility" and new means of deriving insight from previously siloed data opens up new possibilities for applications. Specifically, they may help redefine how people access, pay for and use transport in their everyday lives.

Although deployment of DLTs is only starting to support MaaS, DLT adoption in the transport sector can be highly relevant for several issues. These include the management of secure identity (of users, operators and service providers) and access management (linked to payment data, certificate or licence information). It also includes authentication, asset identification (available capacity, location, vehicle condition and type, state of repair, etc.) and efficient and secure distribution of information in the MaaS ecosystem.

To maximise the benefits of such a new model, the regulatory framework also needs to evolve. Traditional regulatory approaches focus on transport operators and modes in isolation. These approaches are increasingly out of step with recent market offers and how many people make travel decisions. Public authorities need to adapt their regulatory framework to this emerging and interconnected "mesh-y" urban mobility ecosystem. Legislation has to set the framework for interoperable MaaS but standardisation bodies must still address technical details. The process for setting these standards must be inclusive, transparent and technically thorough. Governments are also called to:

- account for changes in data science and technology when developing MaaS
- look beyond initial cryptocurrency applications of DLTs
- help deploy the building blocks that enable wider uptake of distributed ledgers
- apply blockchain technology now for slow and relatively small transport use cases
- anticipate next-generation DLTs for "big and fast" applications to be deployed later
- develop algorithmic code-based regulation to accompany the uptake of DLTs.

Improved efficiency in the public sector

The use of DLTs in the public sector brings new opportunities for government services. There are around 50 jurisdictions worldwide launching more than 200 DLT-based initiatives (Berryhill, Bourgery and Hanson, 2018[39]). Some of the most common use cases include identity (e.g. credentials or licences), personal records (e.g. health, insurance or financial), land title registries and asset inventory. The public sector can further benefit from the adoption of DLTs in a number of areas. These include supply-chain management, asset tracking and inventorying of goods (e.g. food, medicines or natural resources); management of social benefits, entitlements and aid; management of utilities through smart energy grids; copyrights management; voting; and mitigating and identifying fraud.

Blockchain technology could allow the public service to improve effectiveness, reduce friction between agencies, reduce bureaucratic barriers, better share knowledge and foster automation through smart contracts. However, it also poses challenges to public administrations. Its limitations may render the technology unsuitable for certain uses. The most common challenge relates to data protection, governance and confidentiality of information. Coding constraints and governance decisions also add to the complexity. Finally, the formats of some blockchains have inherent limitations. These include the high levels of energy required to power certain systems, and in some cases the slow pace of transaction processes. Policy makers need to consider these challenges and limitations as DLTs continue to expand in the public sector.

Towards low-carbon infrastructure models

Carbon neutrality is not the most common factor of individuals' perception of blockchain technologies. Bitcoin, blockchain's first application, is widely known as an environmental polluter. It consumes massive amounts of energy and emits vast amounts of CO_2 to validate transactions and sustain the network.

However, concerns of this nature hold true only for certain specific mechanisms in the underlying technology. Depending on network architecture and choice of protocols, blockchain can be deployed in more energy-efficient ways. For example, private blockchains using consensus algorithms like proof-of-authority, when set up properly, do not consume more energy than traditional database solutions. From this perspective, the core competencies of blockchain technology – transparency, data auditability, privacy, value transfer, and process efficiency and automation – can potentially drive the systemic changes needed to deliver sustainable infrastructure (OECD, 2019[40]).

Blockchain technology can unlock new sources of financing and mobilise industry pledges to carbon reduction through new financing platforms. The technology can also bring visibility to alignment with sustainability goals by enabling countries and stakeholders to track data and information on infrastructure projects. Blockchain-enabled platforms are a way to standardise data, assess asset performance and enhance compliance (such as to sustainability or to standards for economic, social and corporate governance). These may be further augmented when integrated with remote sensors (IoT) or linked to deep analytics such as AI applications. Finally, blockchain and DLTs can enhance awareness and access by acting as a transaction-enabling infrastructure of new market models. This can incentivise and increase the willingness and ability of institutions and consumers to help build long-term sustainability, while driving changes within industries to adapt to shifting consumer demand.

To promote this new model, policy makers need to promote an openly accessible, standardised "toolbox" and education materials on blockchain. To that end, they need to facilitate further R&D in the field. They also need to clarify regulatory treatment, particularly in the realm of securities law, tax law, the legal recognition of data stemming from blockchain databases, data privacy and consumer protection. Finally, they need to foster both knowledge transfer to developing economies to generate buy-in from related stakeholders and international collaboration and knowledge sharing more generally (OECD, 2019[40]).

Adaptation of national blockchain strategies across countries calls for a globally coherent approach to DLT innovation and adoption

Governments have evidenced a growing interest in how DLTs are transforming their economies and societies, as well as their use as a tool to deliver policy objectives. A number of countries, both OECD counties and partner economies alike, have already issued overarching blockchain strategies, including Australia, China, Germany, India and Switzerland. Others, including France and Italy, are developing such strategies.

Australia released its National Blockchain Roadmap in February 2020 (Department of Industry, Science, Energy and Resources, 2020[41]). It details how the country plans to realise the (potential future) benefits of blockchain technology. The National Blockchain Roadmap Steering Committee, which includes Australian regulators, will oversee the roadmap.

The roadmap identifies three areas foundational for success with blockchain:

- effective, efficient and appropriate regulation and standards
- skills and capabilities that can drive innovation
- strong international investment and collaboration.

It details the status quo, suggests measures and policies under each area, and provides examples of how the government is using the technology. For instance, the Australian Border Force created the Inter-Government Ledger to enable electronic sharing of import/export documentation internationally. This helps border and customs officials verify the contents of shipments more quickly and to facilitate trade flows (Department of Industry, Science, Energy and Resources, 2020, p. 28[41]).

The Australian roadmap also includes a number of sectoral case studies that demonstrate applications of the technology. It also highlights how the case studies help meet policy requirements. They consider areas such as wine exports; issuance and management of education credentials; and sharing of Know Your Customer information among financial institutions.

Germany released its Blockchain Strategy of the Federal Government in September 2019 (BMWi and BMF, 2019[42]). The strategy identifies blockchain as a tool for the digital transformation and sovereignty of both Germany and the European Union. It aims to become a hub for blockchain development and financing, highlighting the roles of all members of society in its execution (BMWi and BMF, 2019[42]). The German strategy has five pillars, under which 44 measures are to be launched by 2022 with the following aims:

- Secure stability and promote innovations: adopt blockchain in the financial sector.
- Bring innovations to maturity: advance projects and regulatory sandboxes.
- Make investments possible: develop clear, reliable framework conditions.
- Apply technology: digitise public administration services.
- Distribute information: share knowledge, network and co-operate.

Germany aims to use the opportunities in blockchain technology and mobilise areas of potential for digital transformation. It will maintain and grow its young, innovative blockchain ecosystem to make the country an attractive base for development of blockchain applications and for investments in scaling them up. Germany also aims to create a regulatory framework directed at investment and growth, one that enables market processes to work without state interventions and safeguards the sustainability principle. Where blockchain applications can make solutions more user-friendly for individuals and companies, public administration will be the lead application user in individual cases; as a precondition, this should not adversely affect trust in safe, reliable action.

Switzerland released a report – Legal Framework for Distributed Ledger Technology and Blockchain in Switzerland – in December 2018 (The Federal Council, Swiss Government, 2018[43]). Focusing on the financial sector, the Swiss DLT Report describes legal and regulatory frameworks, and outlines a plan to amend them. Among other actions, it proposes to build on the country's status as a hub for FinTech, blockchain and DLT. It also explores the operation and (potential) amendment of civil and insolvency laws, financial market laws and laws combating financial crimes.

This focus is in keeping with the government's efforts to exploit the benefits offered by digitalisation more broadly and make the economy more competitive. The report is guided by the need for relevant frameworks to encourage innovation through market forces. These frameworks should also be based on principles, be technology- and competition-neutral, provide legal certainty and be efficient in their operation.

Switzerland also intends regulatory agencies to be highly receptive to emerging technologies like blockchain and develop close relations with the blockchain sector. In line with the Swiss DLT Report, the Federal Council submitted a proposal to the Swiss parliament in November 2019 to amend banking, corporate and financial infrastructure laws. This move aims to ensure that frameworks can better accommodate blockchain-based systems and assets (The Federal Council, Swiss Government, 2019[44]).

India released Part 1 of Blockchain: The India Strategy in January 2020 (NITI Aayog, Indian Government, 2020[45]). The strategy points to the transformative role of blockchain to deliver public services more efficiently and make it easier to do business. It also highlights how India can deploy blockchain on its digital infrastructure and contains recommendations – which Part 2 of the strategy will describe in more detail – targeted at building India's blockchain ecosystem. The recommendations include creating a "national infrastructure" for blockchain deployment, making India a blockchain research, development and skills hub, and using blockchain in government procurement (NITI Aayog, Indian Government, 2020, p. 52[45]).

The strategy details certain use cases such as land titles management, pharmaceutical supply-chain management, credentialing in the higher education sector and energy trading. In addition, it provides a schema to help identify further use cases for which blockchain would be suitable. In this regard, it states that blockchain is not a catch-all solution for every problem, and devotes a section to "Challenges in blockchain implementation" (NITI Aayog, Indian Government, 2020, p. 26[45]).

In recent years, the Chinese government has also recognised, and worked towards the country's realisation of, the benefits of blockchain. For example, in 2016, it released the White Paper on China's Blockchain Technology and Application Development. It has also included blockchain in the 13th Five-Year National Informatization Plan (Zhao and He, 2020[46]).

In October 2019, President Xi Jinping reinforced the importance of blockchain for China. He stressed the importance of blockchain as a driver of innovation and economic growth, and called for greater investment in, and development of, blockchain applications. The white paper identified building of skills and competencies in blockchain as key, as well as integration of blockchain into the economy with other emerging technologies. Xi emphasised that legal and regulatory frameworks should be conducive to blockchain development and governance embedded into blockchains to prevent misuse (Xinhuanet, 2019[47]).

China has taken additional steps to bolster its blockchain ecosystem. The National Development and Reform Commission announced in April 2020 that blockchain will, among other technologies, soon underpin Chinese information technology systems (Baker, 2020[48]). China launched its Blockchain Services Network – an infrastructure that enables the cheaper, easier development of blockchain applications – for enterprise use around the world (Musharraf, 2020[49]). Further, the Chinese central bank is poised to launch the nation's central bank digital currency, the DC/EP (Zhao and He, 2020[46]; Ledger Insights, 2020[50]).

Several other countries have dedicated regulatory frameworks for blockchain and DLTs under broader national digital strategies (e.g. Mexico, Russian Federation). Estonia identified blockchain as a key enabling technology to implement a national e-Estonia vision outlined in Digital Agenda for Estonia 2020.

At the European level, the EU National Blockchain Strategy was released in September 2019 as part of the EU Digital Strategy and the Digital Single Market. The strategy has five pillars:

- joined-up political vision
- public-private partnerships
- connection of global expertise
- investment in innovation and start-ups
- promotion and enabling of a Digital Single Market framework, interoperable standards and skills development.

Policy makers and regulators need to stay abreast of, and responsive to, the implications of this emerging technological area. On the one hand, it may imply higher productivity, fostering trust and confidence in institutions, and creating highly skilled jobs. On the other, it could enable highly distributed and completely decentralised governance and ease of operation across borders. Further, it may pose important challenges to traditional policy and regulatory frameworks, and governments' ability to control risks for end-users and provide certainty. Providing a timely, global response to these challenges is key. Lack of regulatory certainty was already identified as one of the leading impediments to greater blockchain innovation and mainstream adoption, while lack of global coherency opens opportunities for regulatory arbitrage.

In 2018, driven by this growing international interest and the OECD's own research and analysis from the perspective of government, OECD countries agreed to establish the Global Blockchain Policy Centre. The centre aims to support governments to better understand this technology; address the challenges raised by DLTs and their applications; and seize opportunities to achieve policy objectives and deliver more effective government services.

Quantum computing

The theory of quantum mechanics opens a door to new technologies

The theory of quantum mechanics is fundamentally different from the laws of nature commonly accepted as inarguable truths. It has peculiar features and nuances, such as the theories of superposition and non-locality. This is often explained in lay terms as particles being "in different places at the same time".

Initially founded in quantum mechanical theories, the notion of a quantum computer arose from the idea that humanity could use these more complex laws of nature to develop technology that could solve problems beyond the capacity of "normal" or "classical" computers.

Quantum mechanics opens a door to a range of new technologies for different purposes. One such purpose is "sensing", the field that uses quantum systems for high precision measurements of magnetic fields, electrical fields, gravity and temperature. Other potential targets are quantum timekeeping, global positioning, signal processing, cryptography and solutions to computational problems. This section will focus on the latter (Box 11.4).

Quantum computers provide an advantage for specific computational tasks

According to scientific consensus, a (universal) quantum computer should be programmable to perform any computational task allowed by the laws of physics. This notion can be best understood by comparing a classical computer to a calculator. A classical computer can be programmed to perform any desired task, while a calculator can only perform limited predefined calculations. The news media define a quantum computer more broadly to include machines that only perform a set of predetermined tasks. In one example of such a machine, the Canadian company D-Wave Systems commercialised the quantum annealer. This section will use the term quantum computer widely to refer to any form of quantum technology designed to perform computational tasks.

Box 11.4. Qubits

The unit for data storage in a quantum computer is called a qubit. This is an extension of the bit, which is the unit for data storage of a classical computer. A qubit can take the two binary values 0 and 1, as well as a range of values in between, through the quantum mechanical phenomenon of superposition.

To solve computational problems that are of interest, a quantum computer needs a minimum number of qubits. This number depends on the complexity of the problem and the efficiency of the algorithm.

To achieve impact, a quantum computer needs sufficient computational power (Box 11.5). Current quantum computers serve as a proof-of-concept that the technology can be built. However, they lack the power to offer an advantage over classical computers for any real-world application. Furthermore, errors occur frequently. This is referred to as "noise" in the computation. To distinguish the current small-scale quantum computers from ideal quantum computers, the latter will be labelled as "large-scale fault-tolerant quantum computers".

Unlike some popular science reports might suggest, a quantum computer is not a magic machine that provides additional computational power. It is faster than classical computers only at performing specific tasks. As a result, it has the potential to address certain computational problems, which are intractable on the most powerful supercomputer, and any future classical computer. For other tasks, discussed below, it could provide a significant speed-up.

Quantum computers are not the answer to all computational problems. Some tasks have good solutions on neither a classical nor a quantum computer. This class of problems is called "NP-hard" problems.

An example of such tasks is the famous travelling salesman problem. One solution would be to find the shortest possible route that visits each of a number of selected cities and ends at the city of origin. One could check the length of every possible route, but this takes too long as the list grows broader and broader. As the theory suggests, quantum algorithms that tackle this problem have only a small computational benefit over classical ones (Moylett, Linden and Montanaro, 2017[51]).

Other tasks that are simple on a classical computer, such as copying a piece of data, are complex and difficult on quantum computers. Therefore, quantum computers are unlikely to become machines that consumers will buy individually; instead, they will be used in combination with classical computers and purchased by governments and corporations to perform those tasks for which they offer a competitive advantage.

Box 11.5. Computational power

Most applications need a high number of qubits that operate together in a controlled way. This is a huge technological challenge. A qubit needs to be isolated from any outside interference to maintain its quantum features. The more qubits need to operate together, the harder this task becomes. Failing to achieve sufficient isolation or control, results in errors in the computation, also referred to as "noise".

If individual qubits are sufficiently accurate, there are various techniques to detect and correct errors. These error correction codes use up some of the available qubits, causing fewer qubits to be available for the actual computation. The power of a quantum device therefore depends on the combination of the number of qubits and their reliability. This determines the amount of "fault-tolerant" or "logical" qubits: the qubits available for computation after the error correction. A quantum computer with error rate of 0.1% per computational step requires about 15 000 physical qubits to obtain one fault-tolerant qubit (National Academies of Sciences, Engineering, and Medicine, 2019[52]).

Hundreds to thousands of qubits are required to run interesting quantum algorithms. To run the same algorithm without errors, even more qubits are needed to account for the error correction.

Quantum computers promise both economic gains and political disruption

The development of quantum computers is expected to have a substantial effect both socially and economically throughout the world. A report by the Boston Consulting Group predicts productivity gains by end-users of quantum computing to surpass USD 450 billion annually, reaching USD 850 billion in 2050. These predicted gains include both cost savings and revenue opportunities. They assume that significant technological hurdles can be overcome, and that power and reliability of quantum processors will continue to increase. In the short term (2020-24), they anticipate gains between USD 2 billion and USD 5 billion (Langione et al., 2019[53]).

Long-term benefits are expected in multiple industries, beginning with the financial sector. Big gains are also expected in industries that rely on material design, such as chemical and pharmaceutical companies. Additionally, major disruptions are expected in the area of (cyber) security and defence.

Quantum computers are expected to accelerate chemical research, leading to advancements in commercial areas such as agriculture, drug development and energy, as well as auto and airplane manufactures (Box 11.6).

Understanding and predicting the behaviour of substances on the atomic level is essential for the design of new materials and chemical compounds. Chemical experiments are often expensive and sometimes dangerous. Effective computer simulation of chemical processes would allow researchers to test high numbers of potential methods in a short period at low cost. This would allow researchers to focus on the most promising approaches.

Such physical and chemical simulations have been proven impossible on classical computers on cases involving roughly more than a hundred atoms. Quantum computers are naturally better suited for this task due to their quantum mechanical nature. In recent years, effective quantum methods for physical and chemical simulation have been discovered (Hamiltonian simulation). This could solve some of the most challenging problems in theoretical chemistry and physics, including the elucidation of various complex reaction mechanisms. Deploying quantum computers for physics and chemistry simulation would lead to large economical gains. These gains are achieved through cost savings due to more efficient R&D and manufacturing, as well as higher revenue from superior products.

Before physics and chemistry can be simulated on a quantum computer, further development of quantum hardware is needed. This is still on the horizon as it requires large-scale, fault-tolerant quantum computers. For specific tasks, the algorithms may be improved so that they can be run on near-term quantum computers. This is the case for certain materials, where some interactions between electrons can be ignored or easily approximated.

Quantum computing remains at an early stage for many sectors

Quantum computing holds promise for many sectors, including agriculture, energy and health care, but further research is needed.

In agriculture, access to fertilisers is essential for producing enough food for a growing population. Nearly all fertilisers are made out of ammonia, which requires high heat and pressure to produce. More efficient production of ammonia (or a substitute) would make fertilisers cheaper and could save energy. Little progress has been made because the number of possible catalyst combinations to do so is infinite. While quantum computing could lead to new discoveries, algorithms for this task have not been developed yet.

Improving the capacity, cost, size and charging speed of batteries is essential for renewable energy to replace fossil fuels. Batteries are needed to store solar and wind energy and to power electric cars. Many battery materials pose environmental and humanitarian risks. Various simulation algorithms for small molecules have been developed and tested on quantum computers as a proof-of-concept. However, results simply replicate those achieved on a classical computer. IBM and Daimler, as well as Mitsubishi Chemical and various start-ups, are conducting research in this area.

Efficient molecular simulation could increase our understanding of the interactions and effects of drugs on a range of diseases. In future, this could consider each person's unique genetic composition, potentially leading to more personalised medicine. As genes are unique, this process is not suitable for traditional medical experiments. In the longer term, quantum computing could provide the answer.

Many other sectors would benefit from enhancement of the materials used, such as transport, aerospace, (renewable) energy, consumer goods and packaging. The design of new materials requires understanding of their structure at the atomic level. Simulation of these materials by quantum computers allows researchers to test various possibilities before building them in the lab. This makes progress cheaper and faster. Interest in quantum computers in these sectors is slower than in the chemical and pharmaceutical industry. However, Airbus has invested in quantum software and hardware, and a handful of start-ups is dedicated to relevant industry-specific software.

Major reforms are needed to protect national and cybersecurity from quantum computers

Successful development of powerful quantum computers will break widely used encryption protocols for data authenticity and security. It requires large-scale reform to ensure national and cybersecurity throughout the world.

Once they are powerful enough, quantum computers can be used to break Rivest-Shamir-Adleman (RSA) cryptography and other encryption methods. RSA cryptography is based on finding prime factors of large numbers, which is hard to do on a classical computer. In the mid-1990s, Peter Shor designed a quantum algorithm that can perform prime factorisation efficiently (Shor, 1994[54]). Using this algorithm can break RSA cryptography and other popular methods of cryptography. Other encryption protocols are believed to be relatively secure against attacks by a quantum computer. In recent years, much interest exists in such "post-quantum" cryptography methods.

Quantum computers powerful enough to run Shor's algorithm are still far away. Many encryption protocols use numbers with 1 024 to 2 048 bits. According to experts (National Academies of Sciences, Engineering, and Medicine, 2019[52]), it will take at least a decade to break protocols based on 2 048 bits.

Various other quantum technologies could play a key role in defence, such as quantum radars. A quantum radar is an emerging technology to detect objects such as stealth aircraft despite background noise. It is robust against radio frequency signals emitted to saturate the radar with noise or false information. The United States, Canada and China have explored quantum radars.

Quantum mechanics gives rise to a new form of encryption which is, in theory, unbreakable. This contrasts with classical encryption methods, which rely on mathematical problems that can be solved, but are too hard to solve within a reasonable time.

Quantum encryption methods use the quantum mechanical phenomenon of "entanglement" between particles to establish a shared "random secret key" between two distant parties. This key, known only to them, is used to encrypt and decrypt messages.

Financial institutions, telecom companies and governments have developed quantum encryption devices for data centres. While the mathematical protocol for encryption is unbreakable, the underlying technology may still be vulnerable to attacks. The first prototype of quantum encryption was developed in 1984 but could be hacked by interpreting the sounds made by the power supplies to control the different settings. As explained by one of its inventors, Gilles Brassard: "So, we could literally hear the photons as they flew, and zeroes and ones made different noises. Thus, our prototype was unconditionally secure against any eavesdropper who happened to be deaf!" (Brassard, 2005[55]). Technology has developed since, making it harder for hackers, but this illustrates the vulnerability of implementing advanced technology in the real world. Ensuring the security of encryption methods and trying to break them is ongoing.

Box 11.6. Analogue and gate-based quantum computers

There are two types of universal quantum computers. Analogue quantum computers include quantum annealers, adiabatic quantum computers and direct quantum simulation. They perform computations by manipulating quantum systems without breaking these up into primitive operations. For their part, gate-based quantum computers break down the computation into a number of primitive operations that can be performed; such computers are analogous to classical computers.

There are two drawbacks to analogue quantum computers. First, the theoretical analysis of the computation speed turns out to be challenging for certain analogue algorithms. As a result, the actual benefit is still unknown. Second, it is not well understood how to guard analogue quantum computers from errors that naturally occur in any real-life set-up.

In addition to general-purpose quantum computers, there are dedicated analogue machines, such as quantum annealers. These are built to solve specific problems, like the simulation of certain chemical processes. Such hardware can be much simpler, but the application and the simulator need to be co-designed.

Quantum computing could increase efficiency of data analysis, forecasting and machine learning

Machine-learning algorithms handle large amounts of data and require a lot of computational power. Therefore, certain tasks may take days, if not weeks or months, to complete. Quantum computers are more efficient at particular subroutines that often occur in machine-learning algorithms (e.g. data classification, regression and principal component analysis). It is therefore believed they will accelerate the field of machine learning in the future.

An example of a quantum application for machine learning is a "recommendation" algorithm that recommends products to an Internet user, based on the preference of other users with similar preferences or online behaviour (Kerenidis and Prakash, 2016[56]). Another application is image recognition, which would allow computers to recognise handwritten symbols, for example (Kerenidis and Luongo, 2018[57]). This has been implemented successfully for a small set of input data on a quantum computer (Li et al., 2015[58]).

There is no indisputable scientific evidence (yet) of quantum machine-learning algorithms that are superior to classical algorithms for real-life purposes. Quantum algorithms improve subroutines, but some benefits are lost for two reasons. First, encoding input data into the quantum computer is inefficient. Second, extracting information from the quantum algorithm is difficult. It is unknown if some algorithms, including those mentioned above, are more efficient than any known classical alternative.

Improvement of such algorithms may accelerate due to developments in quantum software that make the design of quantum code more intuitive. The software company Xanadu has developed a platform for the programming language Python for hybrid quantum-classical computations. This platform makes quantum computing accessible to programmers and allows them to combine machine-learning and quantum algorithms in the same program.

Quantum computers could help solve difficult problems through optimisation

Optimisation is the task to find the best solution among a set of possible solutions. This type of problem is found in various industries – from manufacturing and logistics to financial services. Quantum computers may be better at optimisation problems with a large input set.

Volkswagen launched a pilot project for traffic optimisation using the same techniques. The project uses a quantum computer to calculate the fastest route for nine participating buses in almost real time to reduce passengers' travel time. In contrast to conventional navigation services, the quantum algorithm assigns each bus an individual route. This way, each bus can drive around traffic bottlenecks along the route, avoiding traffic jams before they arise. Further development in this area could help improve general traffic flow within cities. The team found the quantum algorithm for their purpose was shorter than any classical algorithm. However, it took longer to reach the result than using classical means due to time required for encoding the problem onto the quantum computer (Feld, 2019[59]).

A recently developed quantum algorithm (Montanaro, 2015[60]) improves the efficiency of "Monte Carlo simulations". This is a mathematical technique to determine the range of possible outcomes of a decision or a situation, together with the probabilities at which they will occur. It provides a tool to gauge the consequences of different decisions, including the most extreme potential outcomes. Forecasting of multiple scenarios is used in a number of different areas, where classical computing is at its limits.

Telecom providers use forecasting techniques to assess network performance in multiple scenarios aiming to optimise their network infrastructure. Another example are estimates of the probability of cost overruns in megaprojects, and weather forecasting.

In many examples, a lot of value is at stake. Incremental improvements of forecasting models through more efficient quantum algorithms may substantially reduce costs.

Various parties have shown interest in using quantum computing. The Dubai Electricity and Water Authority announced a partnership with Microsoft to develop new quantum-based solutions. They will address energy optimisation and other challenges where classical computers have serious limitations. Despite the interest, no concrete results have been announced. Various telecommunications providers have expressed an interest in quantum computing research, such as Ericsson.

All of the areas mentioned play a role in the financial services sector. Monte Carlo simulation is a common method for determining the Value at Risk, a widely used risk metric for asset portfolios. Depending on the portfolio, this could reduce the run-time from days to hours. Similarly, quantum computers could be used for the optimisation of financial portfolios, trading trajectories and arbitrage opportunities. They can also help determine the likelihood of future asset prices.

Corporations in the financial sector have invested in quantum computing

Various corporations in the financial sector are already investing in quantum computing. Goldman Sachs and Fidelity have invested in the hardware company D-Wave Systems, while RBS, Allianz and Citigroup have invested in software start-ups. Other financial institutions, such as JPMorgan and Chase, have entered a partnership with IBM, while BMO Financial Group and Scotiabank have partnered with Xanadu.

The partnerships aim to build a knowledge base, as well as develop and test quantum algorithms on quantum simulators. In this way, they can be ahead of the curve when quantum hardware has sufficiently matured (Konrad, 2017[61]). Various start-ups operate in the field of financial services. The first software tool, the Quantum Asset Allocator, is already on the market.

More research is needed to prove the value of quantum computing

Determining the actual advantage of a quantum computer in the area of machine learning and data analysis is tedious. Evidence of a quantum advantage in this area is much weaker than in the area of physics simulations and decryption. Projects like Volkswagen's traffic optimisation pilot may give the impression that quantum computers are already changing society. However, more research is needed to determine if the quantum advantage really makes the difference. Just because a quantum computer can be used for a specific task does not mean it is the optimal method. In fact, it may be a complicated way of doing something simple, like purchasing a smart phone to use as a flashlight.

There are ways to prove mathematically that a specific quantum algorithm is superior to any possible algorithm on a classical computer. However, such arguments are hard to prove. Such proof exists for Shor's prime factorisation algorithm and for methods of physics simulation. For most other applications of quantum computers, however, there is only some evidence that the quantum algorithm is more efficient than all known classical algorithms. Since classical computers and algorithms are evolving too, there may be classical solutions developed that perform the same task equally well. In fact, various discoveries of quantum algorithms have led to improvements to classical algorithms for the same task, such as the "recommendation" algorithm described earlier (Tang, 2014[62]).

The examples above also differ from physics simulations and decryption methods in their type of advantage. In some areas, such as physics simulations and decryptions, fault-tolerant quantum computers can solve tasks that are intractable on a classical computer. In other areas, the advantage mostly amounts to a potential increase in speed. In areas with large volumes of input data, even a small increase may enable real-life applications to tasks that would otherwise be too costly or too slow.

While effective quantum computers are on the horizon, further development is needed for real-world applications

The US National Academies of Science published an extensive report on the current state and future potential of quantum computing in 2019. The report identifies key challenges, milestones and conditions for the realisation of the full potential of quantum computers (National Academies of Sciences, Engineering, and Medicine, 2019[52]).

Since 2017, general-purpose quantum computers, with limited computational power and error rates of around 5%, have been available on the market. This is a major milestone in the development of quantum computers, demonstrating it is physically possible to build this type of hardware. Specific-purpose quantum computers (quantum annealers) have been on the market since 2011 and have scaled more rapidly.

Despite these recent breakthroughs in quantum hardware, most applications described in the previous section require more powerful and more reliable quantum computers than currently exist. In fact, powerful classical computers can perform all meaningful tasks at least as well as a quantum computer, including applications for quantum annealers. Hence, there is no real advantage at present in using a quantum computer – special or general purpose – over a classical computer.

Will quantum computers ever become a game changer in our societies and economies? Governments and investors repeatedly ask this question. Given the number of uncertainties on how to build and use a quantum computer of sufficient scale, even a rough estimate would require a crystal ball. Engineering approaches cannot directly scale to the size needed for quantum computers to run known quantum algorithms. This means that many unanticipated challenges may pop up that may not be possible to solve. With this in mind, it is impossible to project a meaningful timeframe. The absence of industry-wide reporting standards also make it difficult to track progress. Nevertheless, it is unlikely that development is fast enough for quantum computers to break cryptography standards within the next decade.

While industry estimates are often more optimistic, large-scale, fault-tolerant quantum computers seem years away. IBM has set yearly targets for achieving a quantum advantage in the next decade. They define such an advantage as a definite demonstration that a quantum computer offers a significant performance advantage over today's classical computers at a practical level (Gambetta and Sheldon, 4 March 2019[63]).

There are various ways to use quantum mechanical systems (see Boxes 11.6, 11.7 and 11.8) to build quantum computers. Each has its own benefits and challenges. It is unclear which will be the most successful and cost-effective; investment in various options is necessary.

Achieving three milestones would advance the potential of quantum computers

Realising the potential of quantum computers requires achieving several intermediate milestones. First, researchers must demonstrate an advantage for the quantum computer by using it to solve a problem that stumps a classical computer. Second, it must achieve commercial success by demonstrating a quantum advantage for a task that has a practical purpose. Finally, it must achieve successful error correction for limited quantum devices.

Demonstrating a quantum advantage is around the corner. In 2019, Google announced it had executed a computational task on its quantum computer in 200 seconds. The same task on a state-of-the-art classical supercomputer would take 10 000 years. Some caution is needed with such claims. As Google points out, a classical computer may be able to perform the same task using sophisticated ways that have not yet been discovered. In fact, IBM claims it can perform the same task in 2.5 days, taking advantage of untapped potential in classical computers (Pednault et al., 21 October 2019[64]). Hence, a definite proof of quantum supremacy may require stronger evidence, but seems within reach.

While hardware is developed further, researchers need to adapt algorithms to be suitable for the limited quantum computers of the near future. On the one hand, algorithms should be robust to noise and require limited computational power. On the other, they must be sophisticated enough that a classical computer cannot simulate them. They will most likely be adaptations of existing algorithms for specific applications. Instead of finding an exact solution, they use an approximate or heuristic approach. This way, a small error rate may still result in a good solution.

First results are expected in the area of chemistry and physics simulation, optimisation and machine learning. These are areas where non-optimal solutions due to errors are not always a problem.

Machine learning is not an exact science that provides solutions that are either right or wrong. It handles large amounts of real-life data, of which only a fraction captures information essential for the algorithm. Through trial and error, the algorithm distils this useful fraction from the redundant data. For this reason, machine-learning algorithms can handle outputs from quantum algorithms that have some degree of error.

In the area of physics simulations, approximate solutions are the norm due to limitations of classical computers. Many methods for determining certain physical properties, such as energy levels, are based on iterative methods. These turn a crude guess into a more and more improved solution. The iterative process allows to break the algorithm into small steps that require limited computational power. These steps could be enhanced by a near-term quantum computer.

In the area of optimisation, similar methods are used, such as the quantum approximate optimisation algorithm (Farhi, Goldstone and Gutmann, 2014[65]). Depending on the application, an interim solution may be good enough, even if a better solution exists. Horowitz (2019[52]) gives an overview of these results.

Achieving this milestone is of vital importance for the entire ecosystem of quantum computing to stimulate the availability of funding necessary for further research.

To unlock the full potential of quantum computers, methods are needed to eliminate or correct unwanted variations in the physical operations of a quantum computer. For this purpose, a quantum error correction algorithm can emulate a noise-free quantum computer. However, this takes up a substantial amount of the computational power of the device, which is larger when the level of physical noise is higher.

Achieving this, even for small quantum computers, requires lower error rates in quantum hardware, more effective error correction algorithms and more computational power than is available. The first and the last improvements are a matter of engineering, while the design of better error correction codes requires theoretical progress.

Development of small-scale error-corrected quantum computers is a major milestone. They provide the basis for effective development and testing of quantum software. Furthermore, they provide a measure to compare computational power across different hardware technologies (Box 11.7).

Box 11.7. Quantum hardware

To build a gate-based quantum computer, one needs to create physical systems that encode qubits, over which one has sufficient control to carry out computations. There are various potential candidates, out of which two seem particularly promising.

The first is called a "trapped ion system". An ion is an atom or molecule that has a net electrical charge, due to an uneven number of electrons compared to protons. The charge of the ion allows it to be controlled by an electromagnetic field. Qubits are encoded as two internal states of the ion.

The second candidate is a "superconducting qubit". This approach uses the unique properties of superconducting materials to create a circuit that acts as an artificial atom. Isolating superconducting qubits requires them to be cooled to temperatures near absolute zero.

The commercial quantum computing ecosystem is growing due to recent investments

As quantum technology has substantial barriers to adoption, economic benefits are not expected to be spread equally. Besides substantial capital, in-depth technical knowledge is required to put quantum computers to use. Early adopters have the advantage of being able to acquire relevant capabilities and talent. They can also integrate technology into their processes in a timely manner. In this way, they can take full advantage of the benefits following a breakthrough. In recent years, more companies have wanted to get involved in quantum computing.

Three kinds of companies benefit most from quantum computing. The first group spends money or other resources to tackle problems with a high-performance computer. A second group comprises companies where the difficulty of solving simulation or optimisation problems prevent the use of high-performance computing or other computational solutions. The third group spends resources on inefficient trial-and-error alternatives, such as wet-lab experiments or physical prototyping.

As of the beginning of 2020, over 175 public and private companies worldwide were operating in the field of quantum technology. This includes quantum computing consulting firms, manufacturers of components for quantum hardware and classical software for the simulation of quantum computers. Most of these companies were founded in the last five years.[4]

Europe, the United States and China are global leaders in quantum technology

Quantum technology is a global field, with North America and Europe at the forefront. US IT giants IBM, Google and Microsoft, together with a handful of US-based start-ups such as Rigetti Computing and Xanadu, are leading the market in quantum hardware. Canada has a strong presence commercially, with about 20 start-ups, including quantum annealing pioneer D-Wave Systems. Europe has a booming ecosystem of over 60 quantum-related start-ups both in quantum hardware and software. Most start-ups are in Western Europe, with a high concentration (20) in the United Kingdom. There is a handful of quantum-related companies in Asia, most of which are in Japan, China and Singapore. Commercial quantum computing is almost non-existent in South America and Africa.

The commercial activity reflects the global investment. In 2015, the estimated global budget for quantum computing research was EUR 1.5 billion (The Economist, 2017[66]). These investments were concentrated in Europe (EUR 550 million), the United States (EUR 360 million) and China (EUR 220 million).

Since 2015, budgets have increased significantly. In 2019, China announced an investment of CNY 17 billion (EUR 2.2 billion) in a national laboratory for quantum information science (China Daily, 2019[67]). The United States has announced doubling its 2019 annual spending on AI and quantum computing, with a budget of USD 2 billion (EUR 1.8 billion) per year. Various European countries, including the Netherlands, Germany, France and Sweden, as well as the Russian Federation and India, have announced additional investments of several hundred million to billions of euro. In addition to government spending, quantum computing start-ups have received EUR 100 million in private investor capital.

Most market leaders in quantum hardware have programmes to stimulate the development, adoption and knowledge of quantum computing across the world. These programmes provide access to their processors, set up networks for collaboration and offer research grants. In this way, they aim to accelerate development of applications for near-term quantum computers and grow the pool of quantum computing talent.

Leaders offer start-ups access to quantum technology

In a major stimulant to the growing ecosystem of quantum start-ups, some quantum hardware companies offer free access to their quantum processor to research institutions and start-ups. Since 2018, IBM has been offering access to their processors, open source quantum software and developer tools to start-ups. As of 2020, they have established global hubs at research institutions in nine different countries, providing each one with a quantum processor. The hubs disseminate the technology to their own members and provide support in advancing and experimenting with quantum computing.

The development of quantum hardware requires a significant amount of resources, specialised knowledge and space. Therefore, it is not likely that most companies and organisations will have physical access to a quantum computer in the near future. However, various companies, such as Rigetti, IBM, Alibaba and D-Wave Systems, provide access to their quantum computers remotely through the cloud. A quantum algorithm can be sent through the Internet to be run on a quantum computer elsewhere, after which the output is sent back. This makes quantum computers accessible anywhere in the world. In 2018, IBM reported 80 000 users of its cloud quantum computing resources, having produced 60 research applications since its launch in 2016 (IBM Research Editorial Staff, 5 April 2018[68]).

Microsoft and Amazon have announced plans to launch cloud-based quantum computing platforms through which users can access different quantum machines. This provides users the flexibility to try out different types of hardware without a commitment. With this growing competition, access and support is likely to become more widespread.

Classical computers have scaled in performance over the last decades. This scaling was fuelled by returns made within the industry. These returns were reinvested in the development of better technology, resulting in higher yields. Long-term funding is necessary to make quantum computers profitable. Until then, funding by governments and investors is required.

Development in quantum computers may be delayed if interest and funding in quantum computing diminishes due to lagging results. This occurred in AI research. In the 1960s, experts predicted intelligent machines would exist within a generation. By the 1970s, however, various governments and investors became disillusioned by the required computer power and stopped funding. The field revived and became successful only when computer hardware had progressed sufficiently at the start of the 21st century.

To maintain the pace of progress, commercial revenue from quantum computers needs to be generated as soon as possible. To this end, real-world applications need to be developed for intermediate-scale quantum computers. That requires algorithms that are robust against noise and require limited computational power. Currently, these do not exist. Until this is achieved, government funding will be essential to prevent a significant decline in development.

Governments stimulate development and prepare for disruptions

The United States is the world leader in quantum computing research, with billions of dollars in funding and around 50 companies and start-ups in quantum technology and services. Various governmental agencies offer funding for quantum computing, including the US Army, the National Security Agency (NSA) and the Department of Energy.

Funding is aimed at practical and commercial uses, as well as fundamental scientific research. Topics range from verifying the fidelity and functionality of intermediate-sized quantum computers to quantum Internet. While most governments only fund domestic research, some US grants are also open to foreign research.

Europe has a long academic tradition of quantum mechanics research, with funding from the European Commission since 1998. In 2018, the Quantum Technology Flagship research initiative was established to develop a solid industrial base to exploit its scientific leadership. The Quantum Technology Flagship has an expected budget of EUR 1 billion over ten years. This complements the spending of individual countries and stimulates international collaboration. The focus is on applications, as well as the basic science behind the technologies.

China is behind the United States on developing universal quantum computers. However, it is on the forefront of space-based quantum communication and cryptography through their Quantum Experiments at Space Scale project. In 2016, the Chinese Academy of Sciences launched the world's first "quantum satellite". The satellite, called Micius, emits signals to different receiving stations in the world to establish a shared random secret key. Initial experiments in China were soon followed by intercontinental quantum cryptography between China and five ground stations in Europe. A team from the University of Vienna and the Austrian Academy of Sciences oversaw the European ground stations (OeAW, 2016[69]).

Since the start of 2020, quantum-enabled secure communication has taken place through a mobile receiving station. Such a station is only 80 kilogrammes in weight and small enough to fit on top of a car. The development of mobile receiving stations was motivated by the demand from users, such as the Industrial and Commercial Bank of China, which already use satellite-based quantum encryption methods. The team plans to make the technology available for commercial clients through the launch of a quantum nanosatellite in the next two years.

China has reportedly made breakthroughs in the area of quantum radars (Thurlby, 2016[70]), which allow detection of stealth aircrafts. According to Chinese state media, China developed and tested the first quantum radar in a real-world environment in August 2016; however, this information cannot be verified.

When it comes to the development of universal quantum computing, China is racing to catch up. The country's 13th Five-Year Plan identifies quantum technology as a focal point for R&D (Wong, 2016[71]). In 2015, the Chinese Academy of Sciences and Alibaba Cloud jointly established the Alibaba Quantum Laboratory, the first quantum computing laboratory in Asia. In 2018, they launched the first free public quantum computing service, accessible through the cloud. Their processor, however, has only a fraction of the computational power of rival services by Google and IBM.

Alibaba's competitor Baidu reportedly announced a USD 15 billion investment in 2018 in its own institute for quantum computing. It is dedicated to the application of quantum computing software and information technology with the aim to become a world-class institution within five years (Borak, 2018[72]).

In addition to the United States, Europe and China, other countries, including India, Israel, Japan, Korea, the Russian Federation and Singapore, have a national agenda to develop quantum computing.

Diverse collaborations spur development of quantum computing

The development of quantum hardware requires significant funds. Consequently, some countries with smaller budgets and less human capital seek to benefit from scientific progress made elsewhere rather than lead scientific development. As such, Israel plans to invest in applications of quantum technology and peripheral hardware. India has announced investment in quantum computing to maintain its technological edge and attract related investments. Such funding programmes are initially geared towards academic research, where most of the knowledge is concentrated.

Developing quantum computers requires a multidisciplinary venture. From building the hardware to implementing the goal functionality, it requires specialised knowledge of material science and engineering, theoretical and experimental physics, as well as software design and programming skills.

As specialised knowledge is concentrated in different places, projects in quantum computing are often collaborations between different research groups from multiple universities and industry partners. This is reflected in national policy for quantum computing. The Russian national strategy, for example, involves over nine universities in different cities. The UK National Quantum Technologies Program funds four dedicated quantum technologies research hubs. These hubs, which collaborate with 26 universities, form the centre of expertise for four different focus areas.

On top of collaborations within the scientific community, quantum computing strategies often involve close ties with industrial partners. Quantum Alliance, for example, is a collaboration between the University of Waterloo and various industry partners. Together, they exchange research ideas and collectively develop quantum technology through focused workshops. In another example, the Quantum Technology Innovation Centre Bristol is a dedicated open-access innovation facility. Businesses can access "pay-as-you-go" incubator labs, office space and state-of-the-art equipment, while being supported by experts in a range of business, technology and manufacturing areas.

Besides national initiatives, international collaborations are sought. As an example, various governments worldwide have entered a partnership with IBM, which installed its machine at the respective governments' university campuses. Through this initiative, IBM hopes to foster quantum computing talent worldwide by providing access to the newest quantum technology.

The collaborative attitude of quantum developers worldwide is beneficial to the speed at which the field develops. For quantum computing to become successful, every aspect of the ecosystem needs to be fully developed.

Quantum technology entails a trade-off between computing power and security

Cryptographic algorithms are essential in e-commerce, mobile and online communication, online banking and cloud computing. As described in the previous section, many methods for cryptography that are effective today may be easy to break once large quantum computers are developed. This poses a risk for confidential information. Further, it threatens the integrity and authenticity of public communications, as tampered data could go undetected.

Measures are needed to secure sensitive data against quantum attacks. This is particularly important for data that needs to be kept for years, such as confidential state documents and health care records. Protective measures also prevent intruders from saving data for possible decryption in the future.

Various methods using quantum and classical technology to provide encryption are believed to be secure, even against quantum computers. Confirmation of security would require testing against any possible attack, which is not realistic. In the absence of quantum computers to test the effectiveness of protocols, there is no guarantee of security.

As the use of cryptography is so widespread and systems are interconnected, implementing such methods requires significant time and effort. For example, most websites do not meet the required standards to be quantum-secure. There is often a trade-off between security, and required computational power and transmitted data. Therefore, there is no one solution for all applications, but a balance between security, processing speed and bandwidth.

To set a standard for post-quantum cryptography, in 2015 the European Union started the project PQCRYPTO, which develops cryptographic techniques. In the same year, the US NSA announced it would explore encryption schemes that would withstand a quantum assault. In 2016, the American government founded the National Institute of Standards and Technology. It announced its intention to publish about six effective schemes by 2022 after eight years of testing.

The Open Quantum Safe, an open source project, keeps an overview of post-quantum cryptography methods. Its library also includes a test harness and benchmarking routines to compare performance of post-quantum implementations. If new cryptography methods are not tested thoroughly enough, they can cause an immediate security risk. Therefore, further efforts to test post-quantum cryptography methods are necessary.

Box 11.8. A quantum Internet can combine computational power of computers worldwide

A third strategy to building large-scale quantum computers is by connecting several smaller quantum computers in a network. Such a network is often called the "quantum Internet". In the ideal scenario, different research institutes and companies across the world could combine their resources.

For this to work, connections between the quantum computers need to preserve the quantum mechanical properties. Hence, ordinary communication signals are not sufficient. This act of preservation can be done with light signals through an optical fibre. However, such light particles are difficult to control and errors are hard to eliminate. Various research groups in the United States, Austria, Japan, China and Switzerland have established short-distance light particles. Cambridge University, in the United Kingdom, recently reported a city-wide quantum network on existing fibres with high-bandwidth data traffic. These networks have been deployed to establish secure communication and do not allow transmission of the resources needed yet for a quantum Internet. In China, the network has already been used for communications between banks in Shanghai and Beijing.

Long-distance communication is hindered due to signal loss. To combat signal loss, many researchers are developing "quantum repeaters". These are devices that capture and amplify the quantum signal.

An alternative to optical fibre networks is a "free space" network, which establishes the connection through a line of sight between two parties. This form of quantum communication is possible between a satellite and the ground, as demonstrated by the Chinese Academy of Sciences (Wong, 2016[71]).

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Notes

1. *www.oecd.ai*.
2. *www.oecd.ai*.
3. The terms "blockchain" and "DLTs", although referring to slightly different concepts, will be used interchangeably in this publication, for the sake of simplicity.
4. For an overview of companies, see *www.quantumcomputingreport.com*.

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