ANNEXES A-4

ARTIFICIAL INTELLIGENCE & DATA, AND BLOCKCHAIN

SG:D TECHNOLOGY ROADMAP
INFOCOMM MEDIA DEVELOPMENT AUTHORITY

CONTENTS

1 INTRODUCTION & OVERVIEW

AI has consistently been cited as one of the key technology areas with the potential to affect every aspect of the digital world, and is also one of the four frontier technology focus areas identified by IMDA to lay a strong foundation for information communication media for Singapore [1]. In Gartner's 2018 emerging technology hype cycle, which identifies 35 promising technologies which could unlock a competitive advantage for companies over the next 5 to 10 years, AI is prominent across the hype cycle, with predictions that AI technologies will virtually be everywhere over the next 10 years [2]. AI has also been identified by Accenture to have the potential to double annual economic growth rate in 12 developed economies and boost labour productivity by up to 40% by 2035 [3].

Blockchain, on the other hand, is still in the early phase of adoption, and Gartner suggests that the technology is another 5 to 10 years away from mainstream. Accenture's Technology Vision 2018 report indicates that technology-driven partnerships are the new-new to drive growth in today's digital economy, and blockchain is a major key for businesses to create, scale and manage these partnerships [4].

2 MARKET STUDY

2.1 Global Market Potential of AI

Gartner projects that global business value derived from AI is expected to total US$1.2 trillion in 2018, an increase of 70% from 2017, and AI-derived business value is forecast to reach US$3.9 trillion in 2022 [5]. *Table 1* illustrates Gartner's forecast of global AI-derived business value till 2022:

	2017	2018	2019	2020	2021	2022
Business Value	692	1,175	1,901	2,649	3,346	3,923
Growth (%)	-	70	62	39	26	17

Table 1: Forecast of Global AI-Derived Business Value (billions of USD)

In another report, "Modelling the Impact of AI on the World Economy", McKinsey suggests that AI could add around 16% to global output by 2030, or about US$13 trillion, compared with today.

2.2 Singapore Market Potential of AI

For Singapore, the AI market has the potential to become a US$960 million market in 2022 and US$16 billion by 2030 with a CAGR of 42.2%[a]. This includes a wide range of technologies used to "analyse, organise, access and provide advisory services based on a range of unstructured information" [6], as indicated by *Exhibit 1*.

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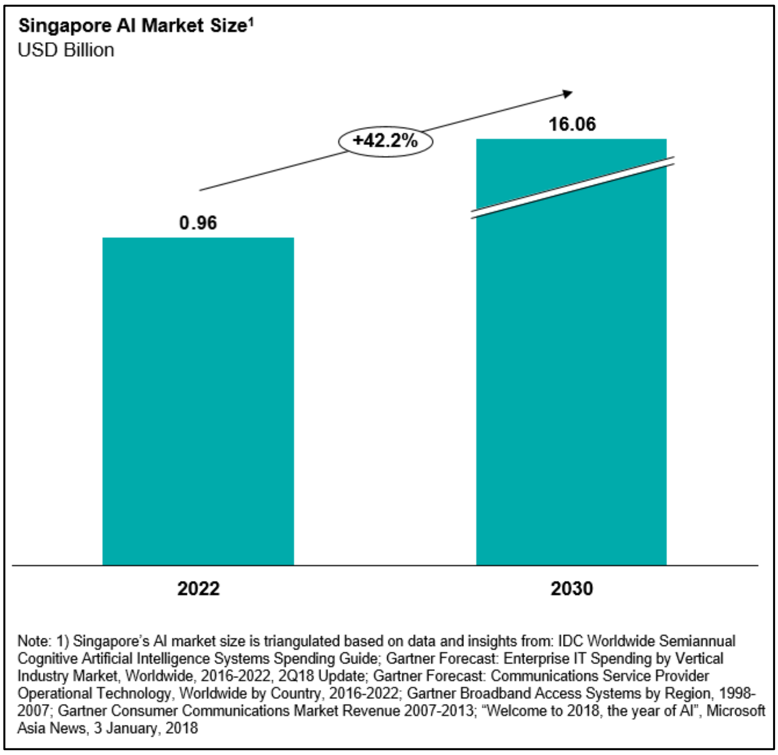
[a] The market forecast for AI and Blockchain is based on the S-Curve. The S-Curve is a mathematical model which produces highly quantitative results, and is applied to various fields such as physics, biology and economics. It is a meaningful model which reflects natural law, and is widely used to analyse specific technologies. The S-Curve is helpful in measuring technological growth at each stage of the life cycle (initial adoption, growth, maturity and decline), and for predicting the timeframe of each life cycle. Hence, by identifying where a technology is at on the S-curve, its future growth and potential can be predicted



Note: 1) Singapore's AI market size is triangulated based on data and insights from: IDC Worldwide Semiannual Cognitive Artificial Intelligence Systems Spending Guide; Gartner Forecast: Enterprise IT Spending by Vertical Industry Market, Worldwide, 2016-2022, 2Q18 Update; Gartner Forecast: Communications Service Provider Operational Technology, Worldwide by Country, 2016-2022; Gartner Broadband Access Systems by Region, 1998-2007; Gartner Consumer Communications Market Revenue 2007-2013; "Welcome to 2018, the year of AI", Microsoft Asia News, 3 January, 2018

Exhibit 1: Singapore AI Market Size

2.3 Global Market Potential of Blockchain (Includes Other Distributed Ledger Technologies)

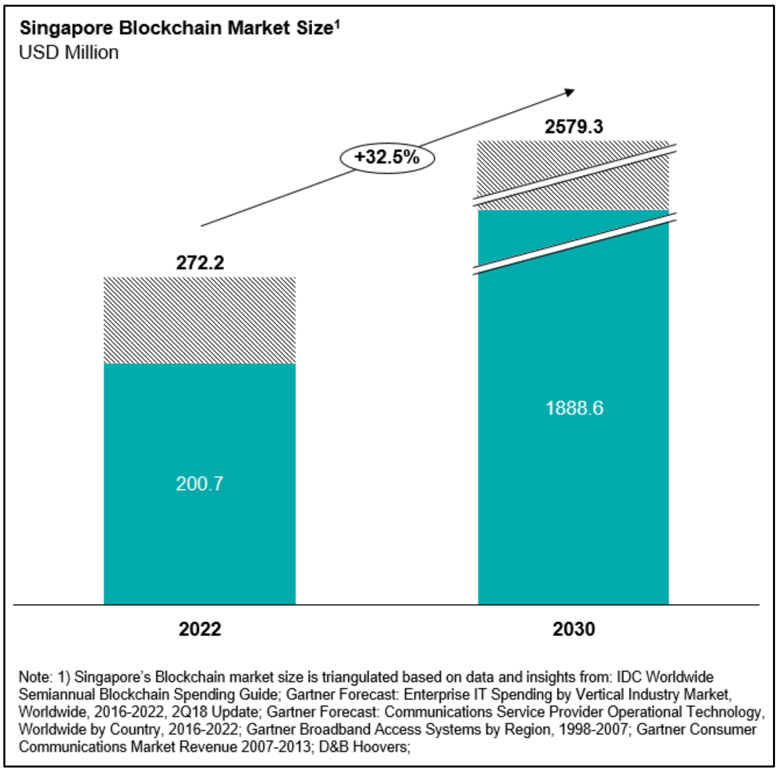
Unlike AI, blockchain is relatively less mature in the diffusion of innovation curve. Gartner's 2018 CIO Survey indicates that blockchain deployments are currently still low – only 1% of CIOs surveyed indicated blockchain adoption – and suggests that organisations should not overestimate the short-term benefits of blockchain [7].

However, there are acknowledgements that blockchain technologies offer a set of capabilities that provide for new business and computing paradigms.

Gartner predicts that blockchain's business value-add will grow to slightly over US$360 billion by 2026, then surge to more than US$3.1 trillion by 2030 [8]. In the longer term, projections indicate that the global blockchain market is expected to grow from US$212 million 2016 to US$8,683 million by the end of 2024, at a Compound Annual Growth Rate of 59.04% [9].

2.4 Singapore Market Potential of Blockchain

For Singapore, the blockchain market has the potential to achieve a range of market spending between US$201 million to US$272 million market in 2022 and US$1.9 billion to US$2.6 billion market by 2030 with a CAGR of 32.5% as indicated by *Exhibit 2*.



Singapore Blockchain Market Size[1]
USD Million

Note: 1) Singapore's Blockchain market size is triangulated based on data and insights from: IDC Worldwide Semiannual Blockchain Spending Guide; Gartner Forecast: Enterprise IT Spending by Vertical Industry Market, Worldwide, 2016-2022, 2Q18 Update; Gartner Forecast: Communications Service Provider Operational Technology, Worldwide by Country, 2016-2022; Gartner Broadband Access Systems by Region, 1998-2007; Gartner Consumer Communications Market Revenue 2007-2013; D&B Hoovers;

Exhibit 2: Singapore Blockchain Market Size

3 TECHNOLOGY STUDY

3.1 Artificial Intelligence

3.1.1 Definition of AI

It is generally agreed that John McCarthy coined the phrase "artificial intelligence" in a written proposal for a workshop in 1956 [10]. AI is now commonly understood as the study and engineering of computations that make it possible to perceive, reason, act, learn and adapt[b].

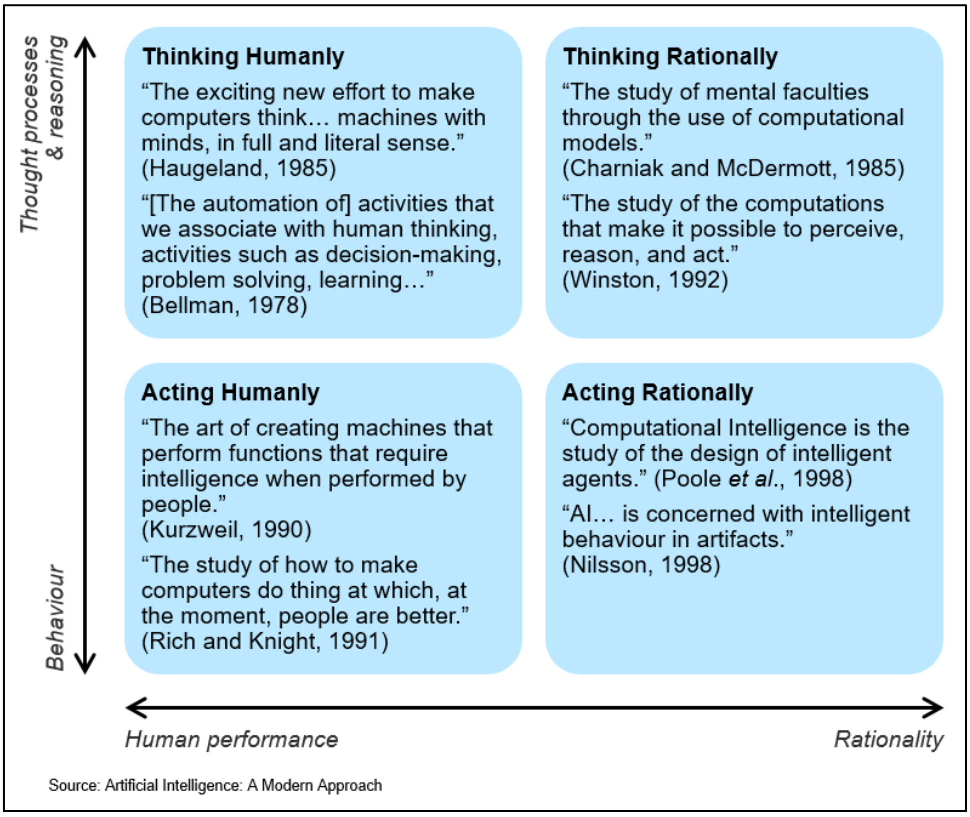
Professor Patrick Winston, Ford Professor of Artificial Intelligence and Computer Science at the Massachusetts Institute of Technology (MIT) defines AI as:

> *"The study of the computations that make it possible to perceive, reason, and act."*

In the widely referenced book, "Artificial Intelligence: A Modern Approach [11]", Dr. Stuart Russell and Dr. Peter Norvig define AI as:

> *"The study of agents that receive percepts from the environment and perform actions."*

The various definitions of AI, laid out along two dimensions are also discussed in *Exhibit 3*. The definitions on the top are concerned with thought processes and reasoning, whereas the ones on the bottom address behaviour. The definitions on the left measure success in terms of fidelity to human performance, whereas the ones on the right measure against an ideal performance measure, rationality:



Thinking Humanly

"The exciting new effort to make computers think… machines with minds, in full and literal sense."
(Haugeland, 1985)

"[The automation of] activities that we associate with human thinking, activities such as decision-making, problem solving, learning…"
(Bellman, 1978)

Thinking Rationally

"The study of mental faculties through the use of computational models."
(Charniak and McDermott, 1985)

"The study of the computations that make it possible to perceive, reason, and act."
(Winston, 1992)

Acting Humanly

"The art of creating machines that perform functions that require intelligence when performed by people."
(Kurzweil, 1990)

"The study of how to make computers do thing at which, at the moment, people are better."
(Rich and Knight, 1991)

Acting Rationally

"Computational Intelligence is the study of the design of intelligent agents." (Poole *et al.*, 1998)

"AI… is concerned with intelligent behaviour in artifacts."
(Nilsson, 1998)

Source: Artificial Intelligence: A Modern Approach

Exhibit 3: Definitions of AI

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[b] Presentation by Professor Steven Miller (Singapore Management University) in a corporate AI seminar

3.1.2 Definition of AI Evolution and Branches of AI

3.1.2.1 Type of Intelligence

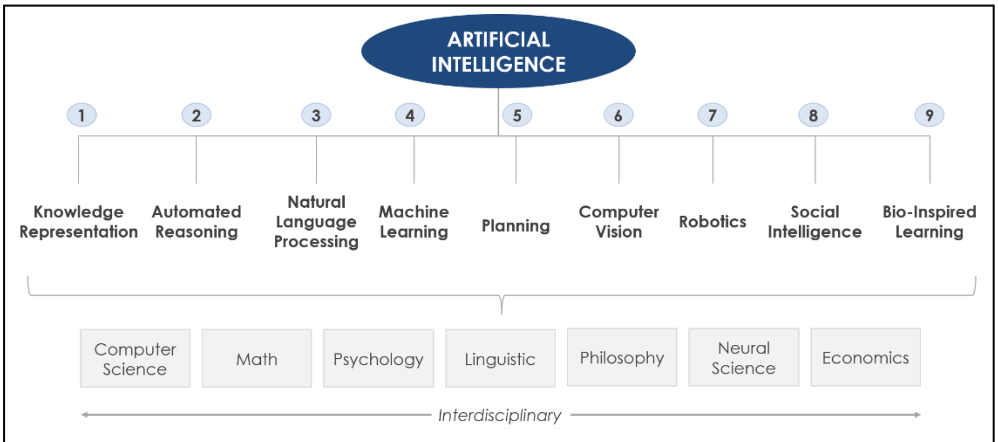
Most of the current advances in AI have been focused on solving particular kinds of problems or narrowly defined tasks. This is generally referred to as “narrow AI”, where the focus is typically on a single subset of cognitive abilities and advances in that spectrum [12]. However, the longer-term goal for many researchers is the creation of “Artificial General Intelligence (AGI)”, which refers to the type of adaptable intellect found in humans, a flexible form of intelligence capable of learning how to carry out vastly different tasks. According to Innovation Centre Denmark, the evolution of AI can be categorised into the three stages [13]:

- ***Artificial Narrow Intelligence (ANI)*** (Today): ANI executes specific focused tasks, without the ability to self-expand functionality. Examples include natural language processing, speech and image recognition, and self-driving. It can outperform humans in specific repetitive functions, such as driving, medical diagnosis and financial advice.
- ***Artificial General Intelligence (AGI)*** (About 2040): AGI, also known as human-level AI, performs broad tasks, reasons, and has capabilities comparable to humans. It might compete with humans across all endeavours, such as earning university degrees, and convincing humans that it is human.
- ***Artificial Super Intelligence (ASI)*** (Soon after AGI): ASI demonstrates intelligence beyond human capabilities. It might outperform humans, helping to achieve societal objectives or threatening human race.

A survey conducted among four (4) groups of expert in 2012/2013 by AI researchers Vincent C Muller and philosopher Nick Bostrom reported a 50% chance that AGI would be developed between 2040 and 2050, rising to 90% by 2075 [14].

3.1.2.2 Branches of AI

The field of AI is vast, and comprises different branches. *Exhibit 4* summarises the branches and approaches of AI, as discussed in this AI technology roadmap:



Source: Adaptation of Taiger Presentation Slide at IMDA AI workshop, May 2018

Exhibit 4: Branches and Approaches of AI[c]

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[c] Adaptation of Taiger presentation slides at IMDA AI workshop, May, 2018

3.1.3 Use Cases and Applications of AI

In 2017, Gartner's hype cycle for emerging technologies highlighted the "AI everywhere" trend [15]. Indeed, the recent few years have witnessed the increasing application of AI in a variety of ways. AI is a pervasive technology whose use cases will apply across many sectors. The intention of this document is not to list down all the use cases. That said, it is worth to highlight the potential of AI to highlight a new paradigm of benefits from AI that was non-existent previously.

- ***Computational Creativity:*** For years, the common wisdom about robots was their role in repetitive, routine jobs; however, projects such as Magenta have applied AI in creative fields such as art [16]. A music album called "I AM AI" that is entirely composed and produced by AI was also released in 2017 [17]. Such developments have triggered a new subfield of AI called "computational creativity", which refers to the study of building software that exhibits behaviour that would be deemed creative in humans [18].

- ***AI in Healthcare:*** AI has also made major strides in sectors such as healthcare. For example, research published by DeepMind indicated that their algorithm was taught to recognise 50 common eye problems, and the algorithm was able to correctly identify the types of eye disease from OCT scans 94.5% of the time, which is on par with expert performance at diagnosing OCT scans [19]. The algorithm was also able to explain how it reached the diagnosis and can be used on more than one type of OCT machine.

- ***AI in Professional Services***: The professional services sector is also transforming with AI in various ways. In legal profession, AI-powered machines and systems, known as lawyer bots, can analyse legal documents, perform due diligence, review contracts, and predict legal outcomes with higher efficiency and accuracy [20]. LawGeex, an example of AI lawyer bot, cuts down the contract review time from 2 hours to 20 minutes using natural language processing to automate contract reviews [21]. AI augments humans' tasks and frees up their time enabling them to focus on a higher-value and more human-skill job such as client advisory and deal negotiation [20]. Similarly, in accounting profession, AI is changing the traditional way of bookkeeping and automating accounting tasks, enabling accountants to focus on advisory roles. This trend can be seen from major accounting software vendors such as Intuit, OneUp, Sage and Xero currently offering capabilities to automate data entry and reconciliations [22].

3.1.3.1 Application and Adoption of AI

Based on McKinsey's global research of AI adoption by sectors, the adoption of AI is relatively uneven across sectors [23]. Based on its overall AI index with key performance indicators (KPIs) across three categories – AI assets, AI usage, and AI-enabled labour, AI adoption revealed to be the greatest in sectors that are already strong digital adopters, such as:

- ***High AI adoption***: High tech / telecom, automotive / assembly and financial services
- ***Medium AI adoption***: Retail, media / entertainment and consumer packaged goods
- ***Low AI adoption***: Education, healthcare and travel / tourism

This provides an indication of the sectors where additional efforts may be needed to encourage AI adoption.

3.1.4 Key/Emerging Developments in AI

3.1.4.1 Algorithms and Techniques

Advancements in AI Innovation

The number of patents granted for AI has been rapidly increasing, increasing more than three-fold from 2012 to 2016 [24]. Such developments are one of the key drivers for the increasingly diverse applications in AI. The following paragraphs provide examples of recent developments that are highlighted in industry articles.

- ***Generative Adversarial Networks (GANs):*** GANs [25] give machines something akin to an imagination, and a widely-publicised example, Nvidia trained a GAN to generate pictures of imaginary celebrities by studying real ones [26].
- ***Capsule Networks (CapsNets):*** First introduced in 2011, CapsNets re-surfaced recently, outperforming Convolutional Neural Networks (CNNs) in data sets that are commonly used for training image processing systems [27].
- ***Swarm AI:*** Swarm AI has also been placed in the spotlight recently, for accurate predictions ranging from sporting events and political events [28] to financial market forecasting [29].

3.1.4.2 Hardware

Investments in AI Hardware

Much of the spotlight has traditionally been on the developments in AI software, such as new algorithms and techniques. However, as AI matures in deployment, there is a growing need for dedicated hardware to provide the computational abilities and/or architecture to make it possible to run AI algorithms within a reasonable period of time and Forbes has coined the phrase “AI is making hardware sexy again [30]”. The AI chipsets market is expected to grow at a CAGR of 35.5% from 2018 to 2025, and reach US$59.26 billion by 2025 [31]. Examples of big corporations who have AI chips strategies include Nvidia, Google, IBM, Microsoft, Huawei, Intel and Amazon [32].

Start-ups in AI chipsets are also fast emerging; some are reportedly valued at close to US$1 billion [33], and others have been able to raise significant funding. Examples include ThinkForce, Cambricon and Graphcore [34].

3.1.4.3 AI Hardware Transition

IBM suggests that the hardware transition from GPUs to the quantum era will happen in three stages [35]:

1. **Current – 2022** : Utilise GPUs, build new accelerators with conventional CMOS
2. **2022 – 2026** : Overcoming the von Neumann bottleneck, analog devices that can combine memory and computation, neuromorphic computing
3. **Beyond 2026** : Quantum computing

Shift Towards Specialised Compute

Table 1 summarises the convergence of AI with hardware developments resulting in a shift towards specialised compute:

Special Purpose Cloud	Chipsets	Edge Compute	Architectures	Complexity in Software
• Google TPU • Microsoft Brainwave • Intel Nervana • IBM Power AI • Nvidia v100	• CPU • GPU • FPGA • Custom ASICs	• Intel neural compute stick • Nvidia Jetson • Nvidia Drive PX	• Cluster compute • HPC • Neuromorphic • Quantum compute	• Model tuning/ optimisation specific to hardware • Growing need for compilers to optimise based on deployment hardware • Workload-specific compute: Model training, inference, etc.

Table 2: Shift Towards Specialised Compute [36]

Hardware developments in quantum computing is also triggering new research in quantum AI, e.g. Quantum Machine Learning (QML) [37], and start-ups looking at using quantum computing to boost machine learning [38].

3.1.4.4 Enablement of Deployment of AI

AI Frameworks

With the exponential demand for AI, and the growth in the size of the AI community, this has led to the evolution of AI frameworks which make learning AI much easier. Notable AI frameworks include TensorFlow, Microsoft CNTK, Caffe, Theano, Amazon Machine Learning, Torch, Accord.Net, Apache Mahout, and Spark MLib [39].

Drag and Drop, No/Low-Code AI Development Platforms

Beyond AI frameworks, tools and platforms that further simplify AI development for business users are also emerging. Google, for example, launched an alpha release of Cloud AutoML, its first in a set of tools that trains AI without requiring code [40]. Start-ups, such as Lobe [41], have also developed AI tools that focus on visual interfaces rather than coding – users use a drag-and-drop interface to build deep learning algorithms [42].

3.1.4.5 Enablement of Trust in AI

As AI increasingly becomes more pervasive and plays an expanding role in society, there is a need to build trust in AI. To trust computer decisions, there is a need to know how an AI system arrives at its conclusions and recommendations.

Typical causes of learned bias in models [43] include algorithmic bias (e.g. training data is not representative), and human bias (e.g. historical inequity captured in data). Forrester suggests the FAIR framework for ensuring models developed are FAIR [44] – Fundamentally sound, Assessable, Inclusive, and Reversible.

Explainable AI

DARPA, for example, is investing in the Explainable AI (XAI) programme [45] to create a suite of machine learning techniques that:

i. Produce more explainable models, while maintaining a high level of learning performance; and
ii. Enable human users to understand, appropriate trust, and effectively manage the emerging generation of artificially intelligent partners.

Algorithmic Audit Tools, Services and Frameworks

Algorithm audit is a growing area as companies increasingly opt-in to such a process in order to gain their customers' trust [46]. Such demand has also driven the availability of algorithmic audit services (e.g. O'Neil Risk Consulting and Algorithmic Audit started by Cathy O'Neil, author of "Weapons of Mass Destruction") and tools (e.g. Accenture AI fairness tool [47]). IBM is also proposing a Supplier's Declaration of Conformity to be completed and voluntarily released by AI developers and providers to increase the transparency of their services and to engender trust in them [48].

3.1.5 Technology Adoption Readiness Map

The technology adoption readiness map intends to inform the stakeholders on which technologies are expected to become mainstream in the coming years globally. A consistent time frame has been used in the narrative – now to 2 years (short-term), 3 to 5 years (mid-term) and beyond 5 years (long-term). Broadly,

- Technologies included in the now to 2 years timeframe are already or expected to be viable for adoption by the majority of industry players in now to 2 years (short-term);
- Technologies included in the 3 to 5 years timeframe have shown evidence of promising use cases, are being provided and afforded by a handful of companies but still not viable for mass adoption. These are expected to be viable in the next 3 to 5 years (mid-term);
- Technologies included in the beyond 5 years timeframe are mostly in the R&D stage and remain inaccessible to industry players. These are expected to become viable beyond 5 years (long-term).

The table below reflects industry's view on the likely evolution and mainstream adoption of AI technology:

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
GENERAL TRENDS			
GENERAL	• Narrow AI in selected verticals	• Narrow AI in more verticals	• Broad, human-like AI
ALGORITHMS & TECHNIQUES			
KNOWLEDGE REPRESENTAION	• Knowledge representation for specific domains, e.g. search applications	• Graph analytics • Knowledge graphs	• Ontology learning
AUTOMATED REASONING	• Automated reasoning for specific domains[d]	• Integration of sensor networks, signal processing and machine	• General automated reasoning

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[d] Reasoning on data and providing analysis to complement human professionals in decision making process in specific domains and use cases, e.g. medical diagnosis and prediction

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
		learning to support decision-making for applications	
NATURAL LANGUAGE PROCESSING	- Natural language Q&A in specific domains[e] , e.g. enterprise chat bots - Speech-to-speech translation in specific domains, e.g. lifestyle devices such as Google Home, Amazon Alexa - Image captioning in specific domains[f] - Natural sounding text to speech[g] - Summarisation in specific domains, e.g. computer-generated news stories	- Text-to-text general translation, e.g. over various context and languages, e.g. Google Translate - Speech recognition for specific domains[h] - Natural language generation	- Combination of natural language processing and computer vision, e.g. visual question answering[i] - Natural language interaction[j] - Advanced speech recognition, e.g. mixed languages, overlapping speeches, noisy environment - Summary generation from multiple sources[k]
MACHINE LEARNING	- Predictive analytics - Ensemble learning[l] - Deep learning for specific applications, e.g. game-playing (AlphaGo), computer vision (CNNs), speech recognition &	- Transfer learning in specific domains, e.g. learning from training in simulation could be applied to physical robots	- Prescriptive analytics - Generative Adversarial Networks (GANs) for specific applications - Lean and augmented data learning

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[e] Systems that automatically answer questions posed by humans in a natural language, and are generally trained using domain-specific data

[f] Uses a combination of computer vision and natural language processing technologies to provide a short description of what is in an image

[g] Aims to mimic and replicate human voice, and reproduce audio words that may not have been spoken by human subjects

[h] Speech recognition engines generally work well with clear speech, quiet environment and when trained using targeted application corpus

[i] AI systems that allow questions to be posed in a natural language about images or a video sequence

[j] The ability to converse on both general and specific topics with an AI agent

[k] Automatically summarise various related articles or documents in a coherent manner without repeating the points and paraphrasing the articles or documents

[l] Use of multiple learning algorithms to obtain better predictive performance compared to the use of any of the constituent learning algorithms alone

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
	synthesis (LSTM models) • Reinforcement learning for specific applications, e.g. computing gaming		• One-shot or zero-shot learning • Robust deep learning, e.g. capsule networks • Extreme learning machines • Training AI systems to develop other AI systems, e.g. automated machine learning and deep learning[m]
PLANNING	• Dynamic and real-time planning, scheduling and optimisation, e.g. in-vehicle routing and optimising goods delivery, with real-time data input of traffic conditions		
COMPUTER VISION	• Real-time gesture recognition for specific applications • Facial and object recognition	• Real-time multi-object and relation detection • Image recognition on extremely large images	• Activity recognition – Understanding the context of the environment as the same actions in different context may have different meanings

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[m] Examples – Google Cloud AutoML uses several machine learning techniques to automatically build and train a deep-learning algorithm

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
ROBOTICS	• Robotic systems for systematic & mundane tasks, e.g. robots in warehouses, autonomous delivery drones	• Assistive robots capable of basic interactions with humans[n] , e.g. robots for customer service in banks and retail, delivery robots in hotels and hospitals	• Hybrid teams of autonomous agents[o] (different vendors & software) acting in collaboration across large geographic areas
SOCIAL INTELLIGENCE	• Limited social intelligence, e.g. inference of human emotion through face analysis[p]	• Enhanced social intelligence, e.g. inference of human emotion through multi-modal inputs[q]	• Simulation of human traits, e.g. human emotional intelligence [49]
BIO-INSPIRED LEARNING		• Swarm intelligence and evolutionary computational techniques[r] for specific applications, e.g. scheduling	
ENABLEMENT OF AI DEPLOYMENT			
AI FRAMEWORKS	• Enhancements of AI frameworks for CPU, GPU and/or low-power environments[s]	• Adaptation of AI frameworks for FPGA[t]	

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[n] This would require robotic systems to sense and process sensory information (machine perception), perform basic interactions with humans and assist in simple tasks to improve human productivity

[o] Even among the branches of AI, there are convergence of technologies e.g. in robotics & self-driving cars, different branches of AI come together

[p] Examples – Microsoft Face API, deepai.org

[q] Examples – Multi-modal emotion AI

[r] Evolutionary computation refers to a set of techniques that is inspired by the natural evolution processes – The algorithms generally consist of principles such as mutation, crossover, reproduction, cloning, survival of the fittest and is a population-based method

[s] Examples – TensorFlow roadmap for TensorFlow 2.0 indicates support for distributed environment (multiple GPUs and TPU cores), GPU optimisation, TensorFlow Lite for low-power environments

[t] Examples – Adapting TensorFlow for FPGA, FPGA acceleration of Convolutional Neural Networks (CNNS), Intel OpenVINO toolkit with FPGA support

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
AI ENABLEMENT SOFTWARE	• AI developer toolkits[u]	• Abstracted, higher-level AI toolkits and software[v] for less experienced developers and/or tech-savvy business users • Training AI systems to develop other AI systems, e.g. automated machine learning and deep learning	• Highly abstracted, AI-assisted AI toolkits for business users[w]
ENABLEMENT OF TRUST IN AI			
AI GOVERNANCE	• Organisation-level frameworks & guidelines[x]	• Common and standardised industry frameworks & guidelines[y]	
EXPLAINABLE AI		• AI algorithms that support explainability through examples, attention heat maps	• AI algorithms that support explainability through discriminative models, deep neural networks dissection
SOFTWARE TOOLS AND SERVICES	• Tests and tools[z] assessing fairness and/or bias in data input, algorithms, etc.	• Algorithmic audit services[aa]	
AI HARDWARE [50]			

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[u] Examples – TensorFlow, Microsoft CNTK, Caffe, Theano, Amazon Machine Learning, Torch, Accord.Net, Apache Mahout, Spark MLib

[v] Example – Google Auto ML for developers with limited machine learning expertise, Lobe drag-and-drop GUI for building deep learning algorithms (Note: Acquired by Microsoft in Sep 2018)

[w] Example – Drag-and-drop, GUI-driven, AI-assisted design tool for AI algorithms

[x] Example – Google disclosing ethical framework on the use of AI

[y] Examples of initiatives that have already started include Partnership on AI, Singapore Government Advisory Council on the Ethical use of AI and Data

[z] Examples – IBM cloud tool to detect AI bias and explain automated decisions, Microsoft tool to detect AI bias, Accenture Fairness Tool

[aa] Example – O'Neil Risk Consulting and Algorithmic Audit

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
CPU	• AI-optimised CPU[bb]		
GPU	• AI-optimised GPU[cc] • Energy-efficient, low-power GPU accelerators		• Multi-chip module design for GPU accelerators
FPGA		• AI-optimised FPGAs[dd] • Energy-efficient, lower-power FPGA for edge computing applications	• Heterogeneous, adaptive and fast FPGA platform[ee]
ASIC		• AI-optimised ASICs	
NEUROMORPHIC COMPUTING			• Neuromorphic-optimised AI
QUANTUM COMPUTING			• Quantum-optimised AI[ff]

Table 3: Artificial Intelligence technology adoption readiness map

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[bb] Example – Intel's Knights Mill chip is said to offer machine learning performance 4x superior to that of data centre CPUs not optimised for machine learning

[cc] Example – Nvidia's Volta architecture is said to be 12x better at deep learning training and 6x better at inference than the preceding Pascal architecture

[dd] Example – Google Tensor Processing Unit (TPU), Intel Nervana chip, Fujitsu Deep Learning Unit (DLU)

[ee] Example – Xilinx Adaptive Compute Acceleration Platform (ACAP) which is both hardware and software programmable, and can dynamically adapt to various workloads and applications

[ff] Example – Quantum machine learning

3.2 Blockchain

3.2.1 Definition of Blockchain

It is generally agreed that blockchain first made its public debut in the paper “Bitcoin: A Peer-to-Peer Electronic Cash System” written by Satoshi Nakamoto in 2008. Blockchain is the underlying technology behind Bitcoin, and since the publication of the paper, it has developed into one of the most significant technologies with the potential to impact many industries.

The blockchain technology space is at the stage of rapid evolution, and whilst these developments are critical in accelerating innovation, there are also differences in industry usage of terminology, resulting in confusion.

The NISTIR 8202 Blockchain Technology Overview document [51] by National Institute of Standards and Technology, the U.S. Department of Commerce defines blockchain as:

“Blockchains are distributed digital ledgers of cryptographically signed transactions that are grouped into blocks. Each block is cryptographically linked to the previous one (making it tamper evident) after validation and undergoing a consensus decision. As new blocks are added, older blocks become more difficult to modify (creating tamper resistant). New blocks are replicated across copies of the ledger within the network, and any conflicts are resolved automatically using established rules.”

3.2.2 Key Differences between Blockchain and Distributed Ledger Technology

The terminology around blockchain technology can be confusing, and there is a lack of agreement amongst the general public as to whether a blockchain is the same as a distributed ledger technology.

The first blockchains that emerged were closely based on the architecture of Bitcoin, where there is a chain of blocks linked by cryptography and blocks are used as data structures. Subsequently, new database systems that emerged are also often referred to as blockchains, but may not share the main characteristics of ‘traditional’ blockchains, e.g. some are ‘block-less’, others do not broadcast all transactions to each participant, etc. The more generic phrase “distributed ledger technology” emerged as an umbrella term to describe these technologies, but in practice in industry, “blockchain” and “distributed ledger technology” are often used interchangeably.

In the context of this TRM, the broader umbrella of distributed ledger technologies is considered, despite the use of the shorter terminology “blockchain”.

Distributed ledgers are a subset of distributed databases, and blockchains are a subset of distributed ledgers [52]. The differences between distributed databases, distributed ledgers, and blockchains are:

- Distributed databases do not have a central ‘master’ database, and are replicated across multiple nodes and devices that collaborate to maintain a consistent view of the database state.
- Distributed ledgers’ design is premised on an adversarial threat model that mitigates the presence of malicious (i.e. dishonest) nodes in the network, and are designed to be Byzantine fault-tolerant.
- Blockchain is a subset of distributed ledgers that uses a data structure that bundles transactions into a chain of cryptographically linked blocks, and/or more broadly includes the global data diffusion with the broadcast of data to all participants.

3.2.3 Public and Enterprise Blockchains

Table 4 illustrates the main types of blockchain by permission models [52]:

Blockchain types		Read	Write	Commit	Example
Open	Public permissionless	Open to anyone	Anyone	Anyone*	Bitcoin, Ethereum
	Public permissioned	Open to anyone	Authorised participants	All or subset of authorised participants	Sovrin
Closed	Consortium	Restricted to an authorised set of participants	Authorised participants	All or subset of authorised participants	Multiple banks operating a shared ledger
	Private permissioned ('enterprise')	Fully private or restricted to a limited set of authorised nodes	Network operator only	Network operator only	Internal bank ledger shared between parent company and subsidiaries

* Requires significant investment either in mining hardware (proof-of-work model) or cryptocurrency itself (proof-of-stake model)

Table 4: Main Types of Blockchain by Permission Model

Public permissionless blockchains tend to operate in a less controlled environment, requiring the application of cryptoeconomics to incentivise participants to coordinate. Bitcoin and Ethereum are examples of public permissionless blockchain networks.

Private permissioned ('enterprise') blockchains tend to operate in an environment where participants are already known and vetted, and there are typically off-chain legal contracts and agreements to coordinate participant behaviour. Hyperledger and Corda are examples of enterprise blockchains.

3.2.4 Use Cases and Applications of Blockchain

3.2.4.1 Evolution of Blockchain Technology

Although the concept of distributed computing has been around since 1990, the publication of the Bitcoin paper by Satoshi Nakomoto in 2009 introduced blockchain technology to the world, allowing the evolution and diversification of blockchain application [53]. Its early applications in the 2010s were in cryptocurrencies and payment, before extending to the financial market in the mid-2010s. Particularly with permissioned blockchain network solutions and smart contracts [54], the application of blockchain has extended beyond the finance sector, and has since gained recognition for its potential to transform various industries [55].

3.2.4.2 Key Features of Blockchain

According to Credit Suisse, blockchain is associated with key features such as immutability of record, disintermediation of trust, and smart contracts [56]. These features have seen the growth of blockchain being applied in various use cases and industries.

- ***Immutability of record***: Once data is recorded, it becomes translucent, immutable and permanent, enhancing the credibility of the transacted values as well as improving fraud detection. Application areas include public sector records, health records and credit reporting.

- ***Disintermediation of trust***: As trust is shared among the network's stakeholders, the third-party risk is reduced and has become less reliance. Application areas include Foreign Exchange, Crowdfunding and FinTech.
- ***Smart contracts***: These are self-executing, digital performance of contracts, which also leverage on the benefit of blockchain – security, verifiability, and immutability. Application areas include supply chain, leasing and legal.

3.2.5 Key/Emerging Developments in Blockchain

3.2.5.1 Decentralised Architecture

Governance

Distributed systems such as blockchain tend to start with trusted third parties, and in many cases, the decentralisation process determines how trust is distributed over time and how governance may be dynamic. In the absence of a central coordinating party in blockchain's decentralised architecture, governance, i.e. coming to a consensus on decisions amongst decentralised nodes, is one of the most important aspects of blockchain design.

There has been an evolution of blockchain governance over time. First-generation blockchain projects are characterised by unspecified governance mechanisms. In second-generation blockchains, the trend leaned towards off-chain, specific governance structures to handle disagreements [57]. In third-generation blockchains, emerging blockchain projects such as Tezos and Dfinity leaned towards on-chain governance [57]. These developments are spurring discussions on future governance strategies [58], including futarchy, liquid democracy and quadratic voting.

Emerging Multi-Disciplinary Areas

The issues discussed above exemplify the multi-disciplinary foundation of blockchain, e.g. software engineering, distributed computing, cryptography science, and game theory [59].

Cryptoeconomics has been discussed in *Chapter 0*, and is an emerging field spurring research. For example, the MIT Cryptoeconomics Lab was setup to push the research frontier in this field.

The decentralised architecture of blockchains can have implications on how centralised entities maintain control over the activities of disparate people participating in the blockchain. This can have legal implications. For example, national borders become largely irrelevant in large blockchain networks where they are replicated across thousands of nodes all over the world. Such issues are giving rise to "lex cryptographia" [60].

3.2.5.2 Network

In a decentralised blockchain network, in the absence of a central party, consensus mechanisms are used to reach agreement in the network. In public blockchains such as Bitcoin and Ethereum, Proof of Work is commonly used. It provides the economic incentives for miners not to cheat, and it provides the needed security. However, it is challenging to scale (e.g. throughput) as the size of the network increases, and it is also very energy consuming. There are significant developments ongoing to explore alternative solutions for public blockchains to scale up, so that it can open up opportunities for blockchain adoption and deployment in high-throughput applications.

The major approaches are outlined below.

Layer 1

Layer 1 approaches refer to development efforts being explored within the blockchain to improve scalability. These include:

- **Data Structures**: For example, Segregated Witness (SegWit) looks modifying the Bitcoin data structures to improve Bitcoin scalability.
- **Consensus**: For example, Ethereum is expected to transition to Proof of Stake in 2019 [61], and the first release of its Casper implementation was launched in May 2018 [62].
- **Sharding**[gg]: For example, Ethereum is expected to implement sharding over two phases, in 2020 and 2021 respectively [61].

Layer 2

Layer 2 approaches refer to development efforts being explored outside of the blockchain to improve scalability. These include:

- **State channels**[hh]: Examples include Lightning Network that scales Bitcoin using payment channels, Raiden Network that scales Ethereum using state channels, FunFair and SpankChain [63].
- **Side chains**[ii]: Examples include Plasma, which creates “child” blockchains attached to the “main” Ethereum blockchain. Side chains are also one of the means to enable cross-chain interoperability [64].

Alternative Distributed Ledgers

Directed Acyclic Graphs (DAGs) are emerging as potential solutions to overcome the scalability issues of ‘traditional’ blockchains, through a different architecture (a directed graph data structure that uses a topological ordering). Key DAGs that are emerging include IOTA, Byteball and Federa Hashgraph.

Customised Hardware and ASIC-Resistant Consensus

Another emerging development is the emergence of Application-Specific Integrated Circuit (ASIC)-based hardware for mining. Historically, users mined Ethereum using GPUs; however, the emergence of ASICs for mining specific cryptocurrencies have resulted in a certain amount of centralisation as big players such as Bitmain create a higher barrier to entry for casual miners [65].

To mitigate against the threat of centralised control over the cryptocurrency as a result of ASIC mining, some, such as the privacy-centric Monero, updated its mining algorithm, designing ASIC-resistant proof-of-work algorithms and hardforked [66].

Enhancements on Consensus Algorithms

Researchers are also looking into enhancements of consensus algorithms, including AI-based consensus mechanisms, e.g. Proof of AI [67].

3.2.5.3 Security and Privacy[jj]

Blockchains are vulnerable to various attacks and various solutions are being developed to enhance blockchain security and privacy.

End Point/Wallet Security

Access to a blockchain requires both a public and private key, and one of the ways to obtain the private key is to attack the endpoint, or digital wallet, which is typically one of the weakest points in the entire

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[gg] Instead of the full node storing the entire state of the blockchain, nodes are grouped into subsets, and they process transactions specific to that shard, so that the system can process many transactions in parallel, hence improving throughout

[hh] These improve scalability by moving state-altering operations off the chain to achieve improvements in cost and speed

[ii] Side chains are separate blockchains that are attached to its parent blockchain (mainchain)

[jj] Note – Smart contract security issues will be covered in Chapter 3.2.5.4, under ‘smart contracts’

system. Examples of digital wallets offering varying degree of security include Software wallets, Hardware wallets[kk]; and Cold wallets[ll].

Secure Enclaves and/or Trusted Execution Environment (TEE)

A secure enclave is a set of software and hardware features that together provide an isolated execution environment to enable a set of strong security guarantees for applications running inside the enclave [68]. TEEs are isolated, secure processing environments to achieve secure remote computation.

There are both open-source (e.g. Oasis Labs) and commercial efforts in these areas. On the commercial front, Intel Software Guard Extension (SGX) is an architecture extension designed for application developers who are seeking to protect select code and data from disclosure or modification. The application code is placed into an enclave by special instructions and software made available to developers via the Intel SGX SDK.

Smart Contract Security

To be covered in *Chapter 3.2.5.4*, under “Smart Contracts”.

Side Chain Security

Chapter 3.2.5.2 discusses side chains as a means of scaling blockchains through the creation of a separate blockchain that is attached to its parent blockchain. Pegged side chains are used to transfer assets between multiple blockchains. Side chains are responsible for their own security, and if there is insufficient mining power to secure a sidechain, it could be compromised [69]. There is ongoing research to examine side chain security.

Security Frameworks

As blockchains start going into deployment, there is a need to develop the blockchain-equivalent of IT security frameworks and standards. One such example is the PwC China Digital Asset Wallet Security Rating System [70], which is a rating system used for the security assessment of digital wallets.

Blockchain implementation security hardening guides [71] are also starting to emerge, as are blockchain security audit and penetration testing services[mm].

Privacy

Public blockchains are open to anyone to join and participate in the network, and exposes its records of transactions to the nodes in the network. This implies little to no privacy for transactions, which may not be desirable for many enterprise applications or sectors where privacy is a regulatory and legal imperative.

Research is ongoing to develop privacy on blockchains, and the key projects seen as forerunners in this area are Zcash (using zk-SNARKS, a variant of zero-knowledge proof[nn]) and Monero (using ring signatures).

Privacy-Preserving Smart Contracts

To be covered in *Chapter 3.2.5.4*, under “Smart Contracts”.

[kk] These that store the user’s private key offline on a hardware device, protected by a secure chip (or equivalent)

[ll] These are completely offline wallets used for cold storage of cryptocurrencies and other digital assets on the blockchain, and only connect to the Internet to send and receive such digital assets

[mm] Example: Hosho.io

[nn] The next major upgrade for Zcash, Sapling, is expected to feature performance improvement to zk-SNARKS

3.2.5.4 Smart Contracts

Some have described smart contracts as one of the most appealing features of blockchains that would enable more widespread blockchain adoption [72]. However, smart contracts are still relatively nascent and there are still many limitations, e.g. lack of development expertise, code flaws, and security [73].

Facilitating Smart Contracts Creation

- ***Smart Contracts Templates***: Some research efforts examine the design landscape of potential formats for storage and transmission of smart legal agreements, which could pave the way for standardised formats for defining and manipulating smart legal agreements [74].
- ***Automated Generation of Smart Contracts***: Others look into modelling approaches to automate the generation of smart contracts [75].
- ***Smart Contract Tools***: Tools such as graphical smart contract editors are also emerging to make smart contracts easier to create, e.g. EtherScripter, Vyper [76].
- ***Smart Contract Security – Mitigating Against Smart Contracts Vulnerabilities***: By simplifying the process of developing smart contracts and the creation of human-readable code, tools such as Vyper, mentioned above, also help to improve security in smart contracts and enable smart contract code auditability.
- ***Decentralised Application Security Project (DASP)***: Projects such as the DASP have emerged to discover smart contract vulnerabilities.
- ***Security Analysis, Audit and Optimisation Tools for Smart Contracts***: Security analysis tools have also been developed to identify smart contracts with security issues, e.g. Oyente [77], Maian [78] and Zeus [79]. There are also open source projects, such as Mythril, and commercial solutions such as CertiK [80], Quantstamp and Solidified [81].

Privacy-Preserving Smart Contracts

As mentioned in Chapter 3.2.5.3 on “Security and Privacy”, public blockchains are open for anyone to join and participate in the network and exposes its records of transactions to the nodes in the network. This implies little to no privacy for transactions, which may not be desirable for many enterprise applications or sectors where privacy is a regulatory and legal imperative. There is research looking into privacy-preserving smart contracts with the ability to hide inputs from everyone, except the person supplying it, perform some computation without revealing any state, and returning outputs based on the smart contract’s specifications.

AI-Powered Smart Contracts

While AI is currently not widely adopted for smart contracts, AI could potentially be applied to smart contracts. For example, IBM is said to be experimenting with turning smart contracts into “cognitive contracts” that can learn and adapt using AI [82].

3.2.5.5 Blockchain Interoperability

The current blockchain landscape is diverse and fragmented, with many emerging players seeking to provide their respective unique public and private services. Forbes describes the verticalisation trend for blockchains for specific data and information recording uses and suggests the need for a greater degree of connectivity between different blockchains [83]. Industry practitioners also suggest that cross-chain interoperability is the key to mass adoption, and those that can execute it well will become the leaders in blockchain [84].

Cross-Chain Technologies and Initiatives

The key cross-chain technologies to enable blockchain interoperability can be classified into four categories [85]:

i. Notary schemes;
ii. Side chains/relays;
iii. Hash locking and
iv. Distributed private key control.

Examples of cross-chain projects [86] using these technologies include Polkadot, Cosmos, ICON, Wanchain, Fusion, and Block Collider. Some of these cross-chain projects have also come together to evolve blockchain technology and interoperability, e.g. Blockchain Interoperability Alliance (BIA) formed by Aion, Wanchain, and ICON.

3.2.5.6 Post-Quantum Blockchain

Quantum computers are powerful machines that take a new approach, built on the principles of quantum mechanics, to processing information [87]. Quantum computing technologies have been advancing very rapidly, and their strong processing capabilities pose a threat to the cryptographic technologies that underpin the security properties of blockchains.

Recognising that the quantum era is near, there is active research ongoing in the area of blockchains to ensure their security properties are not compromised, even in the quantum era.

Quantum-Proofing New Blockchains

Using Post-Quantum Cryptographic Schemes: Designing quantum-resistant blockchains from scratch would involve the application of post-quantum cryptographic schemes and quantum cryptography. Draft NIST standards for quantum-resistant cryptographic algorithms are estimated to be ready in 2023 – 2025 [88].

Blockchains Using Quantum Cryptography [89]**:** Quantum cryptographic tools may also be used to make blockchains more secure. Examples include:

i. Quantum Random Number Generators (QRNGs);
ii. Quantum Key Distribution (QKD) systems; and
iii. Other quantum tools, e.g. quantum authentication, quantum money, quantum fingerprints.

Quantum-resistant blockchain projects have already been announced. For example, Russian Quantum Centre in Moscow indicated they had developed the world's first quantum-proof blockchain [90], and Quantum Resistant Ledger by the QRL Foundation was launched in Jun 2018 [91].

Quantum-Proofing Existing Blockchains

Replacement of Vulnerable Algorithms: Patching existing blockchains against quantum attacks may be significantly harder than designing quantum-safe blockchains from scratch. The first step is to replace the vulnerable cryptographic primitives with quantum-resistant ones. For example, in the Bitcoin network, there is a need to replace the digital signature scheme with a quantum-resistant scheme and use the latter to sign new transactions. This approach would provide security for future transactions [92].

Secure Transition Strategies. Research is also ongoing to examine secure transition strategies for existing blockchains.

3.2.5.7 Standards Development

RAND Europe was commissioned by the British Standards Institute (BSI) to examine the potential role of standards in supporting blockchain, and the key areas where standards could play a role in supporting blockchain are summarised as follows [93]:

- Standards could play an import role in ensuring interoperability between multiple DLT/blockchain implementations and, in doing so, could help reduce the risk of a fragmented ecosystem
- Using standards to establish a strong consensus on consistent terminology and vocabulary could improve understanding of the technology and help progress the market
- Establishing standards to address the security and resilience of, and the privacy and data governance concerns related to DLT/blockchain could help create trust in the technology
- Standards could play a role in digital identity management and foster end-user trust in the technology
- There are potential opportunities for standards to play a role in sectors where provenance tracking is important
- It may be too early to think about standards related to the technical aspects of DLT/blockchain

RAND Europe also provided the indicative timeframe for the prospective role of standards to support DLT/blockchain [93], which are:

- ***Short term***: Terminology and vocabulary
- ***Medium term***: Security, privacy and data governance, end-user identity and Interoperability
- ***Long term***: Technical aspects and provenance tracking

3.2.6 Technology Adoption Readiness Map

Similar to AI, Technology Adoption Readiness Map was developed for blockchain (refer to *Chapter 3.1.5* for details on Technology Adoption Readiness Map). The table below reflects the industry's view on the likely evolution and mainstream adoption of blockchain technology:

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
GOVERNANCE			
GOVERNANCE MECHANISMS & STRATEGIES		• Off-chain governance mechanisms	• On-chain governance • New governance strategies, e.g. futarchy, liquid democracy, quadrating voting
EMERGING MULTI-DISCIPLINARY AREAS			
MULTI-DISCIPLINES		• Crypto-economics • "Lex cryptographia"	

Categories	**NOW - 2 YEARS**	**3 - 5 YEARS**	**> 5 YEARS**
NETWORK – IMPROVEMENT IN SCALABILITY & THROUGHPUT[oo]			
DATA STRUCTURE	• Increase block size, e.g. Segwit • Segwit v1[pp] • *Segwit2x hard fork*[qq]	• New data structures, e.g. Directed Acyclic Graphs (DAGs), e.g. – Hashgraph – SPECTRE – IOTA – ByteBall	
LAYER 1	Consensus • Proof of Work • *Proof of Stake*[rr] *Sharding* *Implementation of sharding in blockchains, e.g. Zilliqa (2018)*	Consensus • Proof of Stake Sharding Implementation of sharding in key blockchains, e.g. Ethereum over 2 phases, in 2020 & 2021	Consensus Enhancements in consensus algorithms, e.g. AI-based consensus
LAYER 2	*State Channels* *Implementation of state channels in blockchains, e.g.* • *Bitcoin – Lightning Network beta*[ss] • *Raiden Network launch*[tt] *Side Chains*	State Channels Bitcoin – Lightning Network Ethereum – Raiden Network Side Chains Plasma	

[oo] Primarily applicable to public blockchains

[pp] Integrated into Bitcoin network late 2017

[qq] Subsequently called off

[rr] Transition for Ethereum expected in 2019

[ss] March 2018

[tt] Summer 2018

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
	Implementation of side chains, e.g. Plasma Cash initial release[uu] *E.g. Plasma Cash initial release (Jun 2018)*		
HARDWARE	GPU & ASIC hardware for mining	ASIC-resistant consensus, e.g. Monero	
TOKENISATION			
TOKENISATION	*Feature Development* *In private blockchains, e.g. UTXO*[vv] *token for Fabric included in Jan 2018 Hyperledger Fabric paper, R3 said to be supporting enterprise tokens* [94]	Feature Development In private blockchains, e.g. UTXO token for Hyperledger Fabric, enterprise tokens for R3 Application Asset tokenisation on blockchain	
SECURITY AND PRIVACY			
NETWORK SECURITY		Network Security • Hardware trusted execution environment End-User Security • Software wallets • Hardware wallets	Network Security • Side chain security
SECURITY FRAMEWORKS/ GUIDELINES	• *Emergence of* – *Blockchain implementation hardening guides* – *Pen testing*	• Blockchain security frameworks and guides, e.g. hardening • Blockchain security analysis	

[uu] June 2018

[vv] Unspent Transaction Output

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
	– *Blockchain security framework, e.g. Digital Asset Wallet Security Framework*	and testing tools, e.g. pen testing • Commercial blockchain security services, e.g. audit services	
PRIVACY	• *zk-SNARKS implemented in Ethereum in Sep 2017* • *Ring signature introduced as optional feature to Monero in Jan 2017, made mandatory in Sep 2017*	• zk-SNARKS • Ring signature • Secret sharing, threshold secret sharing, secure multi-party computation (MPC)	• Side chain privacy
SMART CONTRACTS			
CODIFICATION	• *Tools to simplify smart contract programming emerging, e.g. Vyper, EtherScripter*	• Graphical smart contract editors	• Cognitive smart contracts
SECURITY	• *Smart contract security analysis research & tools, e.g.* – *Oyente (2016)* – *Maian (2018)* – *Mythril (2017)* – *Zeus (2018)*	• Smart contract security analysis, e.g. – Frameworks and guidelines – Tools • Commercial services, e.g. audit	
PRIVACY	• *Privacy-preserving smart contracts, e.g.* – *Hawk (2016)* – *Ekiden (2018)*	• Privacy-preserving smart contract protocols & platforms	

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
	• *Enigma secret contracts (1.0 in 2018, 2.0 in 2019)*		
PERFORMANCE	• *Smart contract optimisation review services – Built into some smart contract security audit services*	• Smart contract optimisation – Tools – Commercial services	
INTEROPERABILITY			
NOTARY SCHEMES	E.g. Interledger protocol		• Interoperable blockchains • Transition – Frameworks and guidelines – Tools – Commercial services
SIDECHAINS/ RELAYS	E.g. Cosmos, Polkadot, Block Collider		
HASH LOCKING	Hashed Time Locked Contract		
DISTRIBUTED PARENT KEY CONTROL	E.g. Wanchain, Fusion		
POST-QUANTUM BLOCKCHAIN			
QUANTUM-RESISTANT BLOCKCHAINS			• Post-quantum signature schemes • Blockchains using quantum cryptography, e.g. – Quantum Random Number Generators (RNGs) – Quantum Key Distribution (QKD) systems – Other quantum tools

Categories	NOW - 2 YEARS	3 - 5 YEARS	> 5 YEARS
QUANTUM-PROOFING EXISTING BLOCKCHAINS			• Replacement of vulnerable algorithms • Secure transition strategies – Methodologies and guidelines – Tools – Commercial services
STANDARDS DEVELOPMENT			
STANDARDS	• Terminology and vocabulary	• Security, privacy and data governance • End-user identity • Interoperability	• Provenance tracking

* Technologies in *italics* are the technologies that has started to show applications in the market, but not yet to become mainstream (expected to become mainstream in 3 - 5 years)

Table 5: Blockchain technology adoption readiness map

3.3 Convergence of AI and Data, and Blockchain

3.3.1 Enabling Exponential Innovation through Technology Convergence

Deloitte's report on exponential innovation suggests that as boundaries blur and dissolve, exponential innovation cannot be fully described by examining any single technology or sector. Focusing on only one technology or sector can miss the broader impacts and opportunities driven by these converging technologies. It is from their interaction and often-unexpected configurations and reconfigurations that radically new innovations — and disruptions — are emerging [95].

To this end, as technology adoption readiness map are developed for individual technologies such as AI and blockchain, there is also a need to understand the areas of convergence and intersection across AI and data, and blockchain.

3.3.2 Convergence of AI, IoT and Blockchain

CoinDesk suggests that 2018 will see the convergence of AI, Internet of Things (IoT) and blockchain [96] and industry practitioners have also suggested that these three technologies would work together in concert to form the Web 3.0 [97].

3.3.3 Blockchain and IoT

IoT has the potential to connect billions of objects simultaneously which has the impact of improving information sharing needs that result in improving our life. Although there are many benefits to IoT, there are also deployment challenges in the real world due to its centralised server/client model. For instance, scalability and security issues that arise due to the excessive numbers of IoT objects in the network. The server/client model requires all devices to be connected and authenticated through the server, which creates a single point of failure. Blockchain enables the decentralisation of the computation and management processes which can solve many IoT issues, especially security.

Forbes suggests that blockchain could be the way to save IoT [98], whilst Computerworld suggests that IoT could be the killer app for blockchain [99].

Blockchain/IoT players have since emerged, leveraging the complementary nature of these two technology areas to develop products and solutions [100]. Examples include Filament Networks [101], which offers an end-to-end solution that enables self-forming wireless mesh networks over long-range radio, and IOTA [102], a blockchain-based transactional settlement and data transfer layer for IoT.

3.3.4 Blockchain and AI

Forbes suggests that there are three major benefits of combining AI and blockchain [103]:

i. AI and encryption work very well together;

ii. Blockchain can help us to track, understand and explain decisions made by AI; and

iii. AI can manage blockchains more efficiently than humans.

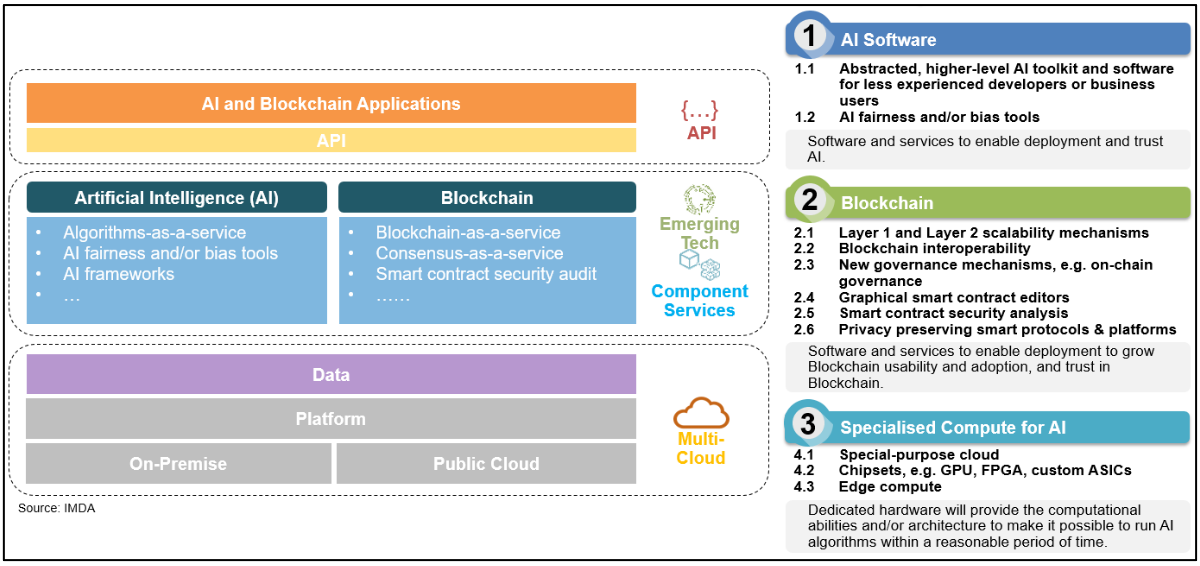
IEE Computer Society suggests that blockchain will bring trustlessness, privacy, decentralisation and explainability to AI; in turn, AI can help build AI systems (e.g. machine learning systems) on blockchain for better security, scalability, privacy-preserving personalisation and automated governance [104].

Blockchain for AI: Players leveraging on the complementary characteristics of AI and Blockchain have already emerged, e.g. Enigma [105] and SingularityNET leverage blockchain to enable secure data sharing and marketplaces for AI.

AI for Blockchain: AI can also enable blockchain technology and implementation, e.g. application of AI to enhance blockchain consensus mechanism (*Chapter 3.2.5.2*), application of AI in AI-powered smart contracts (*Chapter 3.2.5.4*).

3.4 AI, Data and Blockchain Contribution to Cloud Native Architecture

As a part of the overall technology roadmap recommendation, Singapore needs to establish a Cloud Native Architecture to improve access to emerging technologies amongst the stakeholders and assure Services 4.0. We believe that AI, Data and Blockchain technologies will play an important part in ensuring the success of the Cloud Native Architecture as highlighted by the *exhibit* below. *Exhibit 5*, below shows how AI, Data and Blockchain technologies will contribute to various aspects of Cloud Native Architecture.



AI Software

1.1 **Abstracted, higher-level AI toolkit and software for less experienced developers or business users**
1.2 **AI fairness and/or bias tools**

Software and services to enable deployment and trust AI.

Blockchain

2.1 **Layer 1 and Layer 2 scalability mechanisms**
2.2 **Blockchain interoperability**
2.3 **New governance mechanisms, e.g. on-chain governance**
2.4 **Graphical smart contract editors**
2.5 **Smart contract security analysis**
2.6 **Privacy preserving smart protocols & platforms**

Software and services to enable deployment to grow Blockchain usability and adoption, and trust in Blockchain.

Specialised Compute for AI

4.1 **Special-purpose cloud**
4.2 **Chipsets, e.g. GPU, FPGA, custom ASICs**
4.3 **Edge compute**

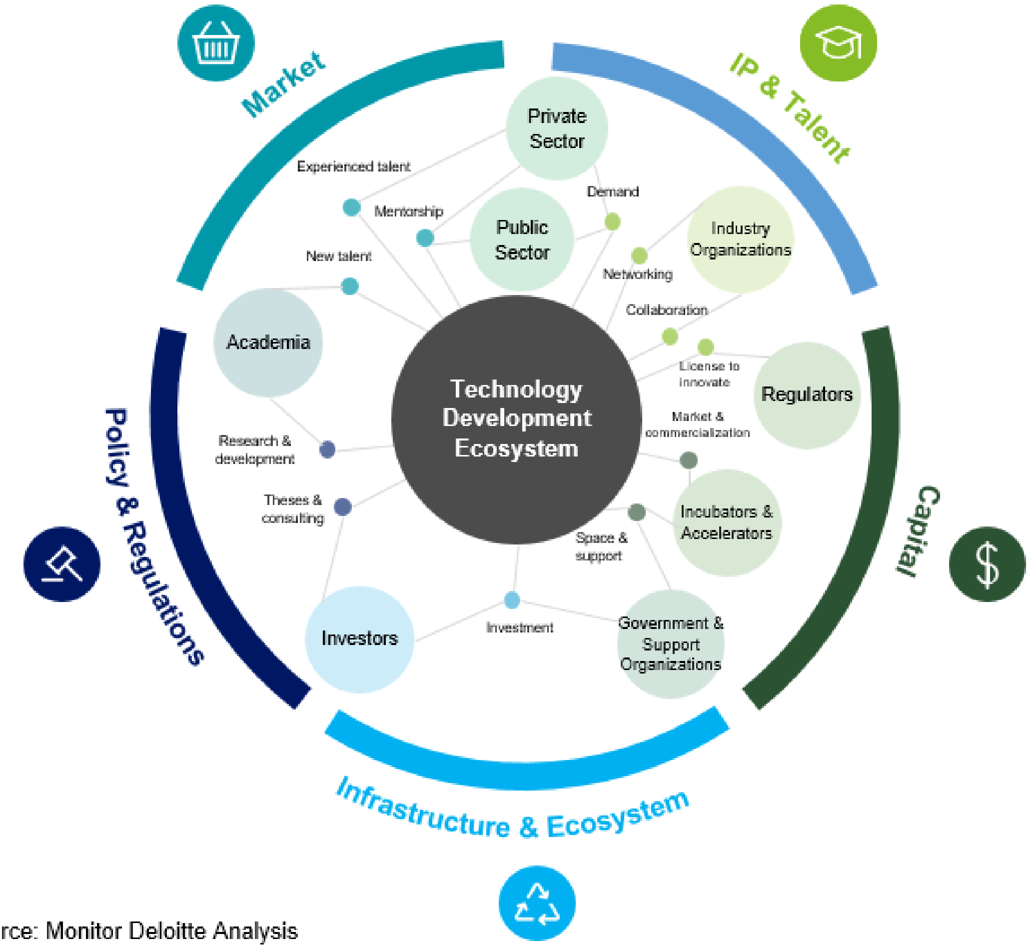
Dedicated hardware will provide the computational abilities and/or architecture to make it possible to run AI algorithms within a reasonable period of time.

Source: IMDA

Exhibit 5: AI, Data and Blockchain Contribution to Cloud Native Architecture

4 SWOT ANALYSIS

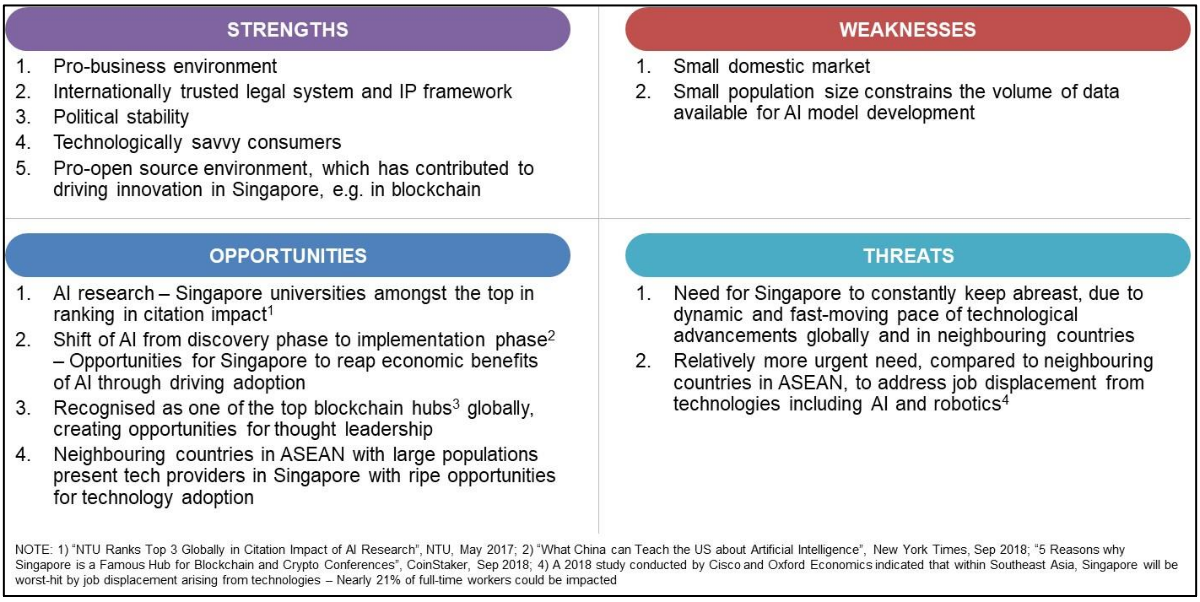
For Singapore to experience the benefits of AI, Data and Blockchain technologies, it is crucial to understand the strengths, weaknesses, opportunities and threats (SWOT) of enterprises and businesses. With this understanding, we can ensure that the findings are relevant to their needs and concerns. The framework shown in *Exhibit 6* allows for a well-rounded analysis of this matter, with the following key criteria; Market, IP & Talent, Capital, Infrastructure & Ecosystem, Policy & Regulations.



Source: Monitor Deloitte Analysis

Exhibit 6: Framework for SWOT Analysis

A SWOT analysis of the Singaporean Landscape for AI, Data and Blockchain revealed the following strengths, weaknesses, opportunities and threats clearly indicating the areas in which Singapore should expend resources in order to become a global player in the area of AI, Data and Blockchain.



STRENGTHS

1. Pro-business environment
2. Internationally trusted legal system and IP framework
3. Political stability
4. Technologically savvy consumers
5. Pro-open source environment, which has contributed to driving innovation in Singapore, e.g. in blockchain

WEAKNESSES

1. Small domestic market
2. Small population size constrains the volume of data available for AI model development

OPPORTUNITIES

1. AI research – Singapore universities amongst the top in ranking in citation impact[1]
2. Shift of AI from discovery phase to implementation phase[2] – Opportunities for Singapore to reap economic benefits of AI through driving adoption
3. Recognised as one of the top blockchain hubs[3] globally, creating opportunities for thought leadership
4. Neighbouring countries in ASEAN with large populations present tech providers in Singapore with ripe opportunities for technology adoption

THREATS

1. Need for Singapore to constantly keep abreast, due to dynamic and fast-moving pace of technological advancements globally and in neighbouring countries
2. Relatively more urgent need, compared to neighbouring countries in ASEAN, to address job displacement from technologies including AI and robotics[4]

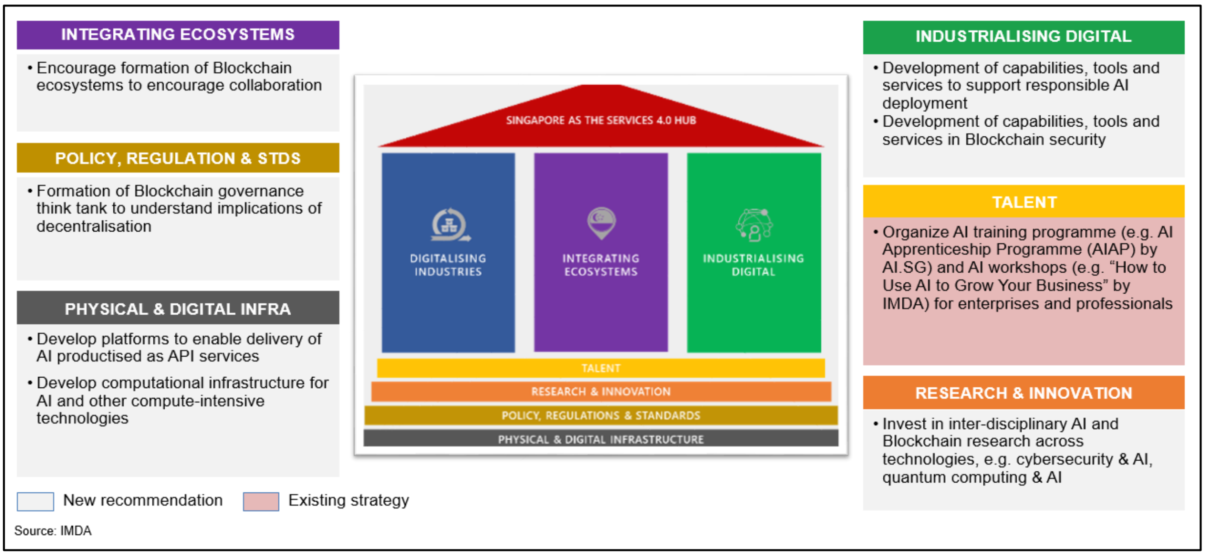
NOTE: 1) "NTU Ranks Top 3 Globally in Citation Impact of AI Research", NTU, May 2017; 2) "What China can Teach the US about Artificial Intelligence", New York Times, Sep 2018; "5 Reasons why Singapore is a Famous Hub for Blockchain and Crypto Conferences", CoinStaker, Sep 2018; 4) A 2018 study conducted by Cisco and Oxford Economics indicated that within Southeast Asia, Singapore will be worst-hit by job displacement arising from technologies – Nearly 21% of full-time workers could be impacted

Exhibit 7: SWOT Analysis [106] [107] [108]

4.1 Conclusion from SWOT Analysis

In conclusion, AI and blockchain technologies require a focused set of strategies, with Singapore's unique strengths and weaknesses in mind. Firstly, interventions need to be devised to accelerate the adoption of AI and blockchain in Singapore to capitalise on the significant potential the technologies can generate in the economy, business and people. Singapore should leverage its pro-business, pro-open source environment and robust legal systems to make AI and blockchain ecosystem into a trusted ecosystem. This will accelerate the adoption of AI further. Whilst AI and blockchain are seeing rapid advancements globally, Singapore should also double down its commitment in investing in specific AI and blockchain R&D opportunities to chalk out its niche in the global market. Specifically, it should have a multi-disciplinary R&D approach towards both AI and blockchain given their unique pervasive impact in the society. Areas around technology convergence would be another topic for Singapore to focus on. Finally, as both hard and soft infrastructure of AI and blockchain are getting more intertwined, Singapore should invest in both these technologies to ensure sustainable capability development and secure its future.

5 RECOMMENDATIONS



INTEGRATING ECOSYSTEMS

- Encourage formation of Blockchain ecosystems to encourage collaboration

POLICY, REGULATION & STDS

- Formation of Blockchain governance think tank to understand implications of decentralisation

PHYSICAL & DIGITAL INFRA

- Develop platforms to enable delivery of AI productised as API services
- Develop computational infrastructure for AI and other compute-intensive technologies

INDUSTRIALISING DIGITAL

- Development of capabilities, tools and services to support responsible AI deployment
- Development of capabilities, tools and services in Blockchain security

TALENT

- Organize AI training programme (e.g. AI Apprenticeship Programme (AIAP) by AI.SG) and AI workshops (e.g. "How to Use AI to Grow Your Business" by IMDA) for enterprises and professionals

RESEARCH & INNOVATION

- Invest in inter-disciplinary AI and Blockchain research across technologies, e.g. cybersecurity & AI, quantum computing & AI

☐ New recommendation ▨ Existing strategy

Source: IMDA

Exhibit 8: Alignment of Recommendations in AI, Data and Blockchain to DE Framework

5.1 Recommendations for AI

The recommendations for AI are outlined below.

5.1.1 Enablement of AI Deployment – Productisation of AI as API Services

Gartner predicts that by 2020, AI technologies will be virtually pervasive in almost every new software product and service [109]. However, the key challenges encountered by AI adopters (e.g. enterprises, or applications and solutions developers looking to incorporate AI in their applications and solutions) typically lie in (i) a lack of access to quality data, and (ii) scarcity of AI scientists to build AI models.

Major cloud players such as Microsoft, Google, AWS and IBM are starting to deploy AI in the form of API services through their cloud platforms, and such developments are expected to democratise AI. Enterprises or applications and solutions developers no longer need to develop these capabilities in-house, but could leverage such cloud-based services to move ahead of their competitors.

Algorithmia was an early player in this, launching their algorithms marketplace in 2015 [110]. The initial AI cloud services tended to be "horizontal" across sectors, e.g. language translation APIs, text-to-speech APIs, speech-to-text APIs, etc. However, this trend has since evolved to sector-specific AI cloud services, such as Azure's Health Bot service [111].

To enable enterprises and applications/solutions developers in Singapore to incorporate AI in their respective organisations, it is recommended for the Government to consider initiatives to encourage potential AI services providers to productise their respective AI solutions as API services, so that AI can be more easily accessible to enterprises and consumers, augmenting on-premise deployments.

5.1.2 Enablement of Trust in AI – Develop Capabilities, Tools and Services to Support Responsible AI Deployment

As Singapore develops its digital economy, a trusted ecosystem is key, where industries can benefit from innovations in technology while consumer confidence and understanding can be assured. A new council was announced in Jun 2018 to advise the Singapore government on the ethical use of AI and data [112].

As guidelines and policies on the ethical use of AI and data are being formulated, it is envisioned that AI adopters could benefit from access to tools and/or services to support responsible AI deployment, so as to grow enterprise and consumer confidence in the technology.

As early as 2016, Google researchers developed a test for machine learning bias [113]. Since then, Facebook has developed Fairness Flow to measure for potential biases for or against particular groups of people [114], and Microsoft is creating an oracle for catching biased AI algorithms [115]. IBM has launched a cloud tool to detect AI bias and explain automated decisions [116], whilst Accenture has launched AI testing services [117].

To enable enterprises and applications/solutions developers in Singapore to support responsible AI deployment, it is recommended for Government to consider initiatives to encourage the development of tools and services to support responsible AI deployment.

5.1.3 Algorithms & Techniques – Invest in Multi-Disciplinary AI Research

AI is an interdisciplinary field, encapsulating knowledge across:

i. Computer science;
ii. Mathematics;
iii. Psychology;
iv. Linguistics;
v. Philosophy;
vi. Neuro-science; and
vii. Economics.

As advancements in this field inches towards artificial general intelligence, there is a need for a multi-disciplinary AI research community in Singapore. It is recommended for Government to consider investing in multi-disciplinary AI research to build up Singapore’s research and development capabilities in these areas.

AI is said to have social and cultural implications, and will create a cultural shift as well as a technical shift [118]. Singapore has been described as a melting pot of cultures where “east meets west”, and it provides a unique environment for such areas of research.

The biggest challenge for Singapore when developing advanced AI systems is finding adequate data to train these systems; this is a challenge as Singapore has a small pool of data to choose from compared to other countries. To overcome this constraint, Singapore should develop AI capabilities that require smaller primary data sets to generate equivalent if not more AI generated insights and other benefits.

5.1.4 AI Infrastructure – Develop Computational Infrastructure in Singapore

The convergence of AI with hardware developments is resulting in a shift towards specialised compute (see *Table 2*).

Some aspects of specialised compute, such as special purpose clouds, may already be available and accessible to enterprises. However, other aspects of specialised compute may be more specialised, and require a greater extent of investments by enterprises.

To enable enterprises and research in Singapore to have easy access to such specialised compute capabilities and resources, there could be a potential need to build up computational infrastructure in Singapore to enable access to specialised compute needed for AI. It is recommended for Government to examine the demand drivers for specialised compute and develop a roadmap for such computational infrastructure in Singapore.

5.2 Recommendations for Blockchain

The recommendations for blockchain are outlined below.

5.2.1 Adoption of Blockchain – Blockchain Governance Think Tank

A poll by EY indicated that regulatory complexity is the greatest barrier to widespread blockchain adoption, whilst regulatory changes are the primary driver of broader integration [119]. The PWC 2018 Global Blockchain Survey also revealed that regulatory uncertainty is the biggest barrier to blockchain adoption [120].

The decentralised architecture of blockchain, particularly public blockchains, has legal, political, economic and social implications on countries, and regulatory agencies globally take on different approaches to this topic [121].

It is recommended for Government to consider the formation of a multi-stakeholder blockchain governance think tank with multi-disciplinary skillsets (e.g. technical, legal and regulatory expertise) to examine the legal and regulatory challenges and barriers for blockchain adoption in Singapore.

However, acknowledging the cross-border nature of global blockchains, and notable ongoing efforts internationally, e.g. Blockchain Regulation Roundtable [122] by Blockchain Research Institute, it is also recommended that Singapore should have regular engagements with international players driving such efforts globally to ensure that Singapore’s approach remains in alignment with that of the international blockchain community.

5.2.2 Adoption of Blockchain – Formation of Business Ecosystems to Encourage Collaboration

Blockchain technology is advancing at an exponential pace, and whilst these developments are critical in accelerating innovation, there is also some fragmentation in the blockchain technology ecosystem due to the number of blockchain platforms, solutions and implementations in the industry.

Cross-chain technologies currently being worked on in the community, and many cross-chain projects exist, and convergence towards common solutions and interoperability standards are expected to take time.

In the meantime, it is recommended for Government to consider initiatives to encourage early adopters in industry to take on a business ecosystem-centric approach in their blockchain pilots and deployments. For example, the Singaporean government should encourage the formation of special interest groups, associations and/or professional bodies across applications and domains to encourage collaboration, as well as discuss and harmonise deployment approaches.

5.2.3 Research and Development – Invest in Multi-Disciplinary Blockchain Research

Blockchain has a multi-disciplinary foundation, involving more than technology, and also taking into consideration design thinking, legality, finance, economics, behavioural science and others.

NUS has announced the creation of the “Cryptocurrency Strategy, Techniques, and Algorithms” or CRYSTAL Centre, an academic research lab and think tank [123], and there are opportunities for Singapore to be at the foremost of research on blockchain.

It is recommended for Government to consider investing in multi-disciplinary blockchain research to build up Singapore’s research and development capabilities in these areas. Examples include promoting research and development in token economy and design thinking, cryptoeconomics, blockchain and the law, etc.

5.2.4 Enablement of Blockchain Deployment – Develop Capabilities in Blockchain Security

As blockchain technology matures and inches towards mass adoption, it is envisaged that blockchain security capabilities will be needed to support blockchain deployment. Examples include blockchain and smart contracts security analysis, hardening, penetration services and optimisation services. Early market players already exist.

It is recommended for Government to consider initiatives to encourage ICT solutions providers to develop capabilities in blockchain security, and offer tools and/or services to support enterprises deploying blockchains.

5.3 Recommendations for Technology Convergence

The recommendations for technology convergence are outlined below.

5.3.1 Multi-Disciplinary Research and Development

Existing research and development efforts in Singapore tend to focus on specific technology pillars. Whilst the need to focus on individual technology pillars remains critical, given the trend towards technological convergence, it is recommended for Government to consider initiatives to encourage the cross-pollination of multi-disciplinary research capabilities to strengthen Singapore's research and development efforts.

Examples include quantum machine learning (refer to *Chapter 3.1.4.2*), an emerging inter-disciplinary research area at the intersection of quantum physics and machine learning, the application of quantum technologies in Blockchain (refer to *Chapter 3.2.5.6*) and the intersection of cybersecurity with other technologies such as AI and blockchain [124].

6 SUMMARY

In conclusion, AI and data, and blockchain are all promising technologies that have the potential to catalyse businesses' digital transformation. As a standalone technology pillar, AI is already a key driver of digital transformation across a wide range of sectors, and there is strong potential for AI to enable business opportunities and economic growth through a strong adoption push economy-wide. Blockchain is relatively less mature, however, its distributed architecture represents a potential paradigm change for businesses, Governments and society in general. Whilst adoption is expected to happen slowly and steadily as the changes it brings gain momentum, it also represents opportunities for early adopters that are able to identify appropriate use cases and applications to monetise from it. Finally, convergence is a powerful strategy for driving innovation, and as boundaries blur and dissolve, the convergence of multiple technology pillars is expected to enable new opportunities for businesses and countries.

APPENDIX A: GLOSSARY

TECHNOLOGY	GLOSSARY
AI & Data	
Automated Reasoning	Automated reasoning helps produce computer programs that allow computers to reason completely, or nearly completely automatically.
Bio-inspired Intelligence	Represents the umbrella of different studies of computer science, mathematics and biology. Specifically, Bio-inspired intelligence is an emerging approach which is based on principles and inspired by biological evolution of nature to develop new and robust techniques applied on machine learning.
Capsule Network	A Capsule Neural Network (CapsNet) is a machine learning system that is a type of Artificial Neural Network (ANN) that can be used to model hierarchical relationships. The approach is an attempt to more closely mimic biological neural organisation.
Computer Vision	A field of computer science that is interested in enabling computers to see, identify and process images in the same way that humans do and then provide appropriate output.
Extreme Learning Machine	The Extreme Learning Machine (ELM) is a feedforward neural net, which means that data only goes one way through the series of layers. The ELM structure does not require the parameters of the net to be tuned. ELMs can be useful for classification tasks, logical regression, clustering and more.
FGPA	An FPGA is an integrated circuit that can be customised for a specific application. Unlikely traditional CPUS, FGPAs are “field-programmable,” meaning they can be configured by the user after manufacturing. FGPAs contain programmable logic blocks that can be wired in different configurations. These blocks create a physical array of logic gates that can be used to perform different operations. Because the gates are customisable, FGPAs can be optimised for any computing task.
Generative Adversarial Network	A Generative Adversarial Network (GAN) is composed of two neural networks: a generative network and a discriminative network. The generative network constructs result from input, and “shows” them to the discriminative network. The discriminative network distinguishes between authentic and synthetic results given by the generative network.
Graphic Analytics	Graph Analytics are analytic tools used to determine strength and direction of relationships between objects in a graph. The focus of graph analytics is on pairwise relationship between two objects at a time and structural characteristics of the graph as a whole.
Knowledge Graphs	Knowledge graphs represent information of entities in a graph network allowing people and computers to process the information in an efficient and unambiguous manner.
Knowledge Representation	A field in computer science that allows information about the world to be represented in a form that a computer system can utilise to solve complex task as such as diagnosing a medical condition or having a dialog in a natural way.

Lean and Augmented Data Learning	These are techniques such as transfer learning (transferring the insights learned from one task/domain to another) or one-shot learning (transfer learning taken to the extreme with learning occurring with just one or no relevant examples) – making them “lean data“ learning techniques. Similarly, synthesising new data through simulations or interpolations helps obtain more data, thereby augmenting existing data to improve learning.
Natural Language Processing	Natural Language Processing is concerned with the interaction between computer and human natural languages; particularly how to come up with computer programs that are able to process and analyse large amounts of natural language data.
Ontology Learning	Ontology learning is the automatic or semi-automatic creation of ontologies including extracting the corresponding domain’s terms and the relationships between the concepts that these terms represent from a corpus of natural language text, and encoding them with an ontology language for easy retrieval.
Planning	Planning in Artificial Intelligence is about decisions made by intelligent creatures like humans, robots or computer programs when trying to achieve a goal. It involves choosing a sequence of actions that will with a high probability transform the state of the world, step by step so that it will satisfy some objective.
Robotics	An interdisciplinary branch of engineering and science that deals with the design, construction, operation, usage of robots as well as computer systems for their controls, sensory feedback and information processing. These technologies are used to develop machines that can substitute humans and replicate human actions.
Blockchain	
Blockchain Interoperability	Characteristic of a computer system or network to interact, exchange and make use of information with an independent, outside system or network.
Consensus Mechanisms	A set of rules in a distributed network used for to agreeing on proposed changes, which will help ensure transactions recorded in the ledger are genuine.
Cryptoeconomics	A system where users of blockchain are given financial and economic incentives to get things done.
Directed Acyclic Graph	Directed Acyclic Graph (DAG) is a network with a number of different nodes confirming transactions. Every new transaction requires the confirmation of at least two earlier transactions before it is successfully recorded onto the network. As volume of transactions increases, more transactions are confirmed and entered, resulting in a distributed web of doubly-confirmed transactions.
Hashed Timelock Contracts	A Hashed Timelock Contract is a type of payments that use hashlocks and timelocks to require that the receiver of a payment either acknowledge receiving the payment prior to a deadline by generating cryptographic proof of payment or forfeit the ability to claim the payment, returning it to the payer.
Lex Cryptographia	A new subset of law/rules that comes about due to the prevalence of blockchain technology.
Off-chain Governance	A decision-making process that first takes place on a social level and is afterwards being actively encoded into the protocol by the developers.

On-chain Governance	On-chain governance rules are hardcoded into the blockchain protocol. Any decisions therefore automatically translates into code.
Proof of Stake	An algorithm where a randomised leader is elected for each block and the elected leader can release the next block. The more stake a party has in the blockchain, the more likely he is to be elected as a leader.

APPENDIX B: REFERENCES

[1] Leong, Charmian. "Singapore's Digital Economy Gunning for Four Key Areas." IMDA. September, 2018. https://www.imda.gov.sg/infocomm-and-media-news/buzz-central/2017/6/singapores-digital-economy-gunning-for-four-key-areas.

[2] The Author Staff Writers Which-50 Has a Floating Pool of Irregular Contributors. "Gartner Hype Cycle: AI Will Be Everywhere in 10 Years." Which-50. August, 2018. https://which-50.com/gartners-2018-hype-cycle-ai-will-be-everywhere-in-10-years/.

[3] Accenture. "Artificial Intelligence Poised to Double Annual Economic Growth Rate in 12 Developed Economies and Boost Labor." Newsroom Main. September, 1970. https://newsroom.accenture.com/news/artificial-intelligence-poised-to-double-annual-economic-growth-rate-in-12-developed-economies-and-boost-labor-productivity-by-up-to-40-percent-by-2035-according-to-new-research-by-accenture.htm.

[4] Daugherty, Paul. "Technology Partnerships: Microservices Architecture for Enterprises - Accenture Tech Vision 2018." Accenture. 2018. https://www.accenture.com/us-en/insight-technology-partners-ecosystem.

[5] "Gartner Says Global Artificial Intelligence Business Value to Reach $1.2 Trillion in 2018." Gartner. April, 2018. https://www.gartner.com/newsroom/id/3872933.

[6] "The 3rd Platform Is Evolving." IDC: The Premier Global Market Intelligence Company. https://www.idc.com/promo/thirdplatform/innovationaccelerators/cognitive.

[7] “Gartner Survey Reveals the Scarcity of Current Blockchain Deployments.” Gartner. May, 2018. https://www.gartner.com/newsroom/id/3873790.

[8] Panetta, Kasey. "The CIO's Guide to Blockchain." Smarter With Gartner. July, 2018. https://www.gartner.com/smarterwithgartner/the-cios-guide-to-blockchain/.

[9] Research And Markets. "Global Blockchain Markets to 2024 - Trends Analysis, Company Usability Profiles & Forecasts." Research and Markets - Market Research Reports - Welcome. April, 2018. https://www.researchandmarkets.com/research/66gs4k/global_blockchain?w=4.

[10] Rodney Brooks. “The Origins of Artificial Intelligence”. April, 2018. https://rodneybrooks.com/forai-the-origins-of-artificial-intelligence/.

[11] Russell, Stuart Jonathan, and Peter Norvig. Artificial Intelligence: A Modern Approach. Boston: Pearson, 2018.

[12] "What Is Narrow Artificial Intelligence (Narrow AI)? - Definition from Techopedia." Techopedia.com. https://www.techopedia.com/definition/32874/narrow-artificial-intelligence-narrow-ai.

[13] "Defining Artificial Intelligence." Defining AI. 2018. http://www.icdk.us/aai.

[14] Heath, Nick. "What Is AI? Everything You Need to Know about Artificial Intelligence." ZDNet. February, 2018. https://www.zdnet.com/article/what-is-ai-everything-you-need-to-know-about-artificial-intelligence/.

[15] Panetta, Kasey. "Top Trends in the Gartner Hype Cycle for Emerging Technologies, 2017." Smarter With Gartner. August, 2017. https://www.gartner.com/smarterwithgartner/top-trends-in-the-gartner-hype-cycle-for-emerging-technologies-2017/.

---

[16] "Computer Creativity: When AI Turns Its Gaze to Art." CBS News. July, 2018. https://www.cbsnews.com/news/when-artificial-intelligence-turns-its-gaze-to-art/.

[17] Galeon, Dom. "The World's First Album Composed and Produced by an AI Has Been Unveiled." Futurism. August, 2017. https://futurism.com/the-worlds-first-album-composed-and-produced-by-an-ai-has-been-unveiled/.

[18] OpenMind, “Artificial Intelligence and the Arts: Toward Computational Creativity”. https://www.bbvaopenmind.com/en/articles/artificial-intelligence-and-the-arts-toward-computational-creativity/.

[19] Burgess, Matt. "Now DeepMind's AI Can Spot Eye Disease Just as Well as Your Doctor." WIRED. August, 2018. https://www.wired.co.uk/article/deepmind-moorfields-ai-eye-nhs.

[20] Marr, Bernard. "How AI And Machine Learning Are Transforming Law Firms And The Legal Sector." Forbes. May, 2018. https://www.forbes.com/sites/bernardmarr/2018/05/23/how-ai-and-machine-learning-are-transforming-law-firms-and-the-legal-sector/.

[21] "LawGeex Contract Review Automation." LawGeex. http://www.lawgeex.com/.

[22] Su, Jean Baptiste. "Why Artificial Intelligence Is The Future Of Accounting: Study." Forbes. January, 2018. https://www.forbes.com/sites/jeanbaptiste/2018/01/22/why-artificial-intelligence-is-the-future-of-accounting-study/.

[23] Bughin, Jacques. "Artificial Intelligence: Next Digital Frontier." McKinsey Global Institute. June, 2017. https://www.mckinsey.com/~/media/McKinsey/Industries/Advanced Electronics/Our Insights/How artificial intelligence can deliver real value to companies/MGI-Artificial-Intelligence-Discussion-paper.ashx.

[24] Fujii, Hidemichi, and Shunsuke Managi. "Trends in Artificial Intelligence Technology Invention." Trends in Artificial Intelligence Technology Invention | VOX, CEPR Policy Portal. June, 2017. https://voxeu.org/article/trends-artificial-intelligence-technology-invention.

[25] Ian J. Goodfellow, Jean Pouget-Abadie, Mehdi Mirza, Bing Xu, David Warde-Farley, Sherjil Ozair, Aaron Courville, Yoshua Bengio. "Generative Adversarial Nets." June, 2014. https://arxiv.org/pdf/1406.2661.pdf.

[26] Giles, Martin. "The GANfather: The Man Who's given Machines the Gift of Imagination." MIT Technology Review. February 2018. https://www.technologyreview.com/s/610253/the-ganfather-the-man-whos-given-machines-the-gift-of-imagination/.

[27] Sabour, Sara, and Nicholas Frosst. "Dynamic Routing Between Capsules." Google Brain. 2017. https://papers.nips.cc/paper/6975-dynamic-routing-between-capsules.pdf.

[28] Miley, Jessica. "This Start-Up Uses Human Swarm Intelligence to Develop AI That Can Predict the Future." Interesting Engineering. March, 2018. https://interestingengineering.com/this-start-up-uses-human-swarm-intelligence-to-develop-ai-that-can-predict-the-future.

[29] "Market Predictions by Swarm AI." Credit Suisse. March, 2018. https://www.credit-suisse.com/microsites/conferences/aic/en/blog/swarm-ai-predictions.html.

[30] Snir, Yair. "AI Is Making Hardware Sexy Again." Forbes. June, 2018. https://www.forbes.com/sites/startupnationcentral/2018/06/21/ai-is-making-hardware-sexy-again/#4901b39b277e.

[31] "Artificial Intelligence Chipsets Market by Technology (Machine Learning, Natural Language Processing, Context-Aware Computing, Computer Vision), Hardware (Processor, Memory, Network), End-User Industry, and Geography - Global Forecast to 2025." Market Research Firm.

February, 2018. https://www.marketsandmarkets.com/Market-Reports/artificial-intelligence-chipset-market-237558655.html.

[32] Lu, Victor, and Michael Sarazen. "Tracking the Transforming AI Chip Market – SyncedReview – Medium." Medium. March, 2018. https://medium.com/syncedreview/tracking-the-transforming-ai-chip-market-bac117359459.

[33] Lynley, Matthew. "The AI Chip Startup Explosion Is Already Here." TechCrunch. December, 2017. https://techcrunch.com/2017/12/24/the-ai-chip-startup-explosion-is-already-here/.

[34] "Tracking the Transforming AI Chip Market – SyncedReview – Medium." Medium. March, 2018. https://medium.com/syncedreview/tracking-the-transforming-ai-chip-market-bac117359459.

[35] Welser, Jeff. "The Future of Hardware Is AI, Says Director of IBM-Research Almaden." IBM Blog Research. December, 2017. https://www.ibm.com/blogs/research/2017/12/future-hardware-ai/.

[36] Geetachauhan Follow. "Distributed Deep Learning Optimizations for Finance." LinkedIn SlideShare. October, 2017. https://www.slideshare.net/geetachauhan/distributed-deep-learning-optimizations-for-finance.

[37] Griffin, Matthew. "New Quantum ML Algorithm Could Revolutionise Quantum AI before It Even Begins." 311 Institute. May, 2018. https://www.311institute.com/new-quantum-ml-algorithm-could-revolutionise-quantum-ai-before-it-even-begins/.

[38] Knight, Will. "A Startup Uses Quantum Computing to Boost Machine Learning." MIT Technology Review. December, 2017. https://www.technologyreview.com/s/609804/a-startup-uses-quantum-computing-to-boost-machine-learning/.

[39] Kothari, Abhishek. "Top 9 Frameworks in the World of Artificial Intelligence." Geekflare. May, 2018. https://geekflare.com/ai-frameworks/.

[40] Fingas, Jon. "Google Tool Lets You Train AI without Writing Code." Engadget. January, 2018. https://www.engadget.com/2018/01/17/google-unveils-automl-ai-training-tool/.

[41] Lardinois, Frederic. "Microsoft Acquires Lobe, a Drag-and-drop AI Tool." TechCrunch. September, 2018. https://techcrunch.com/2018/09/13/microsoft-acquires-lobe-a-drag-and-drop-ai-tool/.

[42] Vincent, James. "It's Easier than You Think to Craft AI Tools without Typing a Line of Code." The Verge. June, 2018. https://www.theverge.com/2018/6/12/17452742/deep-learning-ai-learn-lobe-made-easy-coding.

[43] Purcell, Brandon. "Forrester." The Ethics Of AI: How To Avoid Harmful Bias And Discrimination. February, 2018. https://www.forrester.com/report/The Ethics Of AI How To Avoid Harmful Bias And Discrimination/-/E-RES130023.

[44] Reddy, Trips. "Building Trust in the Age of AI - How Businesses Can Build Fairness into Their Machine Learning Models." Watson. July, 2018. https://www.ibm.com/blogs/watson/2018/07/trust-in-the-age-of-ai-build-fairness-into-machine-learning-models/.

[45] Gunning, David. "Explainable Artificial Intelligence (XAI)." Defense Advanced Research Projects Agency. https://www.darpa.mil/program/explainable-artificial-intelligence.

[46] Hempel, Jessi. "Want to Prove Your Business Is Fair? Audit Your Algorithm." Wired. May, 2018. https://www.wired.com/story/want-to-prove-your-business-is-fair-audit-your-algorithm/.

[47] Peters, Adele. "This Tool Lets You See–and Correct–the Bias in an Algorithm." Fast Company. June, 2018. https://www.fastcompany.com/40583554/this-tool-lets-you-see-and-correct-the-bias-in-an-algorithm.

---

[48] Mojsilovic, Aleksandra. "Factsheets for AI Services: Building Trusted AI - IBM Research." IBM Blog Research. August, 2018. https://www.ibm.com/blogs/research/2018/08/factsheets-ai/.

[49] Kleber, Sophie. "3 Ways AI Is Getting More Emotional." Harvard Business Review. July 31, 2018. https://hbr.org/2018/07/3-ways-ai-is-getting-more-emotional.

[50] "Hitting the Accelerator: The next Generation of Machine-learning Chips." Deloitte. 2017. https://www2.deloitte.com/content/dam/Deloitte/global/Images/infographics/technologymediatelecommunications/gx-deloitte-tmt-2018-nextgen-machine-learning-report.pdf.

[51] Yaga, Dylan, Peter Mell, Nik Roby, and Karen Scarfone. "Blockchain Technology Overview." National Institute of Standards and Technology. October, 2018. https://nvlpubs.nist.gov/nistpubs/ir/2018/NIST.IR.8202.pdf.

[52] Hileman, Garrick, and Michel Rauchs. "Global Blockchain Benchmark Study." Cambridge Centre of Alternate Finance. 2017. https://www.ey.com/Publication/vwLUAssets/ey-global-blockchain-benchmarking-study-2017/$File/ey-global-blockchain-benchmarking-study-2017.pdf.

[53] Chung, Gina. "Blockchain in Logistics." Accenture. 2018. https://www.logistics.dhl/content/dam/dhl/global/core/documents/pdf/glo-core-blockchain-trend-report.pdf.

[54] Szabo, Nick. "Smart Contracts: Building Blocks for Digital Markets." Nick Szabo -- Smart Contracts: Building Blocks for Digital Markets. 1996. http://www.fon.hum.uva.nl/rob/Courses/InformationInSpeech/CDROM/Literature/LOTwinterschool2006/szabo.best.vwh.net/smart_contracts_2.html.

[55] "Banking Is Only The Beginning: 42 Big Industries Blockchain Could Transform." CB Insights Research. August 08, 2018. https://www.cbinsights.com/research/industries-disrupted-blockchain/.

[56] Brennan, Charles, Brad Zennick, and Matthew Yates. "Blockchain 2.0." Credit Suisse Equity Research. January, 2018. https://research-doc.credit-suisse.com/docView?language=ENG&format=PDF&sourceid=csplusresearchcp&document_id=1080109971&serialid=pTkp8RFIoVyHegdqM8EllLNi1z/k8mInqoBSQ5KDZG4=.

[57] Stake, Pool Of. "Revisiting the On-chain Governance vs. Off-chain Governance Discussion." Medium. May, 2018. https://medium.com/@poolofstake/revisiting-the-on-chain-governance-vs-off-chain-governance-discussion-f68d8c5c606.

[58] Ehrsam, Fred. "Blockchain Governance: Programming Our Future – Fred Ehrsam – Medium." Medium. November, 2017. https://medium.com/@FEhrsam/blockchain-governance-programming-our-future-c3bfe30f2d74.

[59] Sultan, Karim, Umar Ruhi, and Rubina Lakhani. "Conceptualizing Blockchain: Characteristics and Applications." June, 2018. https://arxiv.org/pdf/1806.03693.pdf.

[60] Wright, Aaron, and Primavera De Filippi. "Decentralized Blockchain Technology and the Rise of Lex Cryptographia." Research Gate. January, 2015. https://www.researchgate.net/publication/314892724_Decentralized_Blockchain_Technology_and_the_Rise_of_Lex_Cryptographia.

[61] Maloney, Conor. "Ethereum Sharding Slated for 2020: Ethereum Foundation Researcher Justin Drake." CCN. July, 2018. https://www.ccn.com/ethereum-sharding-slated-for-2020-ethereum-foundation-researcher-justin-drake/.

[62] Wilmoth, Josiah. "Ambitious Ethereum Upgrade Casper Receives 'First Release'." CCN. May, 2018. https://www.ccn.com/ethereum-moves-one-step-closer-to-proof-of-stake-as-casper-receives-first-release/.

[63] Satoshi, Priyab. "Introduction to State Channels & Payment Channels." LinkedIn SlideShare. May, 2018. https://www.slideshare.net/PriyabrataDash2/introduction-to-state-channels-payment-channels.

[64] Saini, Vaibhav. "Difference between SideChains and State Channels – Hacker Noon." Hacker Noon. June, 2018. https://hackernoon.com/difference-between-sidechains-and-state-channels-2f5dfbd10707.

[65] Biggs, John. "Ethereum Falls after Rumors of a Powerful Mining Chip Surface." TechCrunch. March, 2018. https://techcrunch.com/2018/03/27/ethereum-has-the-asic-blues/.

[66] Kurokawa, Kay. "Forking for ASIC Resistance: A Monero Case Study – Kay Kurokawa – Medium." Medium. June, 2018. https://medium.com/@kaykurokawa/forking-for-asic-resistance-a-monero-case-study-ecdfb6c9fba2.

[67] Chen, JianWen. "An AI Based Super Nodes Selection Algorithm in BlockChain Networks." Arvix. https://arxiv.org/ftp/arxiv/papers/1808/1808.00216.pdf.

[68] Oasis Team. "Towards an Open-Source Secure Enclave – Oasis Labs – Medium." Medium. September, 2018. https://medium.com/oasislabs/towards-an-open-source-secure-enclave-659ac27b871a.

[69] Ray, Shaan. "What Are Sidechains? – Hacker Noon." Hacker Noon. January, 2018. https://hackernoon.com/what-are-sidechains-1c45ea2daf3.

[70] Cheung, Chun Yin. "PwC China Digital Asset Wallet Security Framework." LinkedIn: Log In or Sign Up. August, 2018. https://www.linkedin.com/pulse/pwc-china-digital-asset-wallet-security-framework-cheung/.

[71] Turvey, Luke."Blockchain Implementation Security. A Hardening How-to." Pen Test Partners RSS. Accessed August, 2018. https://www.pentestpartners.com/security-blog/blockchain-implementation-security-a-hardening-how-to/.

[72] Tkatchuk, Ralph. "Why Smart Contracts Will Bring Blockchain to the Masses." Dataconomy. November, 2017. https://dataconomy.com/2017/11/smart-contracts-will-bring-blockchain-masses/.

[73] Orcutt, Mike. "Ethereum's Smart Contracts Are Full of Holes." MIT Technology Review. March 01, 2018. https://www.technologyreview.com/s/610392/ethereums-smart-contracts-are-full-of-holes/.

[74] Clark, Christopher. "Smart Contract Templates: Essential Requirements and Design Options." Arvix. December, 2016. https://arxiv.org/pdf/1612.04496.pdf.

[75] Frantz, Christopher K., and Mariusz Nowostawski. "From Institutions to Code: Towards Automated Generation of Smart Contracts." 2016 IEEE 1st International Workshops on Foundations and Applications of Self* Systems (FAS*W). 2016. https://papers.christopherfrantz.org/pdf/FrantzNowostawski2016_Smart_Contracts_nADICO.pdf.

[76] Miguel. "Smart Contracts of the Future? Vyper and Plutus." Blockgeeks. https://blockgeeks.com/guides/vyper-plutus/.

[77] Luu, Loi. "Making Smart Contracts Smarter." IACR. 2016. https://eprint.iacr.org/2016/633.pdf.

[78] Nikolic, Ivica. "Finding The Greedy, Prodigal, and Suicidal Contracts at Scale." Arxiv. March, 2018. https://arxiv.org/pdf/1802.06038.pdf.

[79] Kalra, Sukrit. "ZEUS: Analyzing Safety of Smart Contracts." Sematics Scholar. February, 2018. https://pdfs.semanticscholar.org/0be2/6e0b845aaa2ad1377dabd6a9da21bee04af1.pdf?_ga=2.74858967.436655072.1536106955-3625117.1536106955.

[80] "Formal Verification Platform for Smart Contracts and Blockchain Ecosystems." CertiK. https://certik.org/.

[81] "Audit a Contract." Solidified - #1 Audit Platform for Smart Contracts. https://solidified.io/.

[82] Makridakis. "Blockchain: The Next Breakthrough in the Rapid Progress of AI." Robotics and Automation Engineering Journal. March, 2018. https://juniperpublishers.com/raej/pdf/RAEJ.MS.ID.555592.pdf.

[83] Adrian Bridgwater. "Blockchains Are Verticalizing, So We Need Interoperability." Forbes. February 07, 2018. https://www.forbes.com/sites/adrianbridgwater/2018/02/07/blockchains-are-verticalizing-so-we-need-interoperability/#52786c9b7ab9.

[84] Grayblock. "Interoperability - The Holy Grail of Blockchain – Coinmonks – Medium." Medium. June, 2018. https://medium.com/coinmonks/interoperability-the-holy-grail-of-blockchain-eb078e1a29cc.

[85] Deng, Liping, Huan Chen, and Jing ZengLiang-Jie Zhang. "Research on Cross-Chain Technology Based on Sidechain and Hash-Locking." SpringerLink. June, 2018. https://link.springer.com/chapter/10.1007/978-3-319-94340-4_12.

[86] Ludwick, Ibrahim, and Ibrahim. "The Race for Cross-Chain Communication: 11 Projects Working on Blockchain Interoperability." Invest In Blockchain. July, 2018. https://www.investinblockchain.com/blockchain-interoperability-projects/.

[87] "What Is Quantum Computing?" What Is Quantum Computing? - IBM Q - US. https://www.research.ibm.com/ibm-q/learn/what-is-quantum-computing/.

[88] Moody, Dustin. "Update on the NIST Post-Quantum Cryptography Project." National Institute of Standards and Technology (NIST). https://csrc.nist.gov/CSRC/media/Presentations/Update-on-the-NIST-Post-Quantum-Cryptography-Proje/images-media/2_post-quantum_dmoody.pdf.

[89] Gheorghiu, Vlad. "Quantum Proofing the Blockchain." Blockchain Research Institute. November, 2017. https://www.evolutionq.com/assets/mosca_quantum-proofing-the-blockchain_blockchain-research-institute.pdf.

[90] Dockrill, Peter. "Scientists Claim to Have Invented The World's First Quantum-Proof Blockchain." ScienceAlert. May, 2017. https://www.sciencealert.com/scientists-claim-to-have-invented-the-world-s-first-quantum-proof-blockchain.

[91] Bentley, David. "QRL Launches Quantum Resistant Blockchain." Blockchain News. June, 2018. https://www.the-blockchain.com/2018/06/29/qrl-launches-quantum-resistant-blockchain/.

[92] Gheorghiu, Vlad. "Quantum Proofing the Blockchain." Blockchain Research Institute. November, 2017. https://www.evolutionq.com/assets/mosca_quantum-proofing-the-blockchain_blockchain-research-institute.pdf.

[93] Deshpande, Advait. "Distributed Ledger Technologies/Blockchain: Challenges, Opportunities and the Prospects for Standards." May, 2017. https://www.bsigroup.com/LocalFiles/zh-tw/InfoSec-newsletter/No201706/download/BSI_Blockchain_DLT_Web.pdf.

[94] Allison, Ian. “Banks Are Trying to Launch Crypto Assets with R3 Tech” June, 2018. https://www.coindesk.com/banks-trying-launch-crypto-assets-r3-blockchain-tech/.

[95] Hagel, John, and John Brown. "From Exponential Technologies to Exponential Innovation." Deloitte University Press. 2013. https://www2.deloitte.com/content/dam/Deloitte/es/Documents/sector-publico/Deloitte_ES_Sector-Publico_From-exponential-technologies-to-exponential-innovation.pdf.

[96] Jobanputra, Jalak. "2018: The Year Blockchain, AI and IoT Converge." CoinDesk. January, 2018. https://www.coindesk.com/2018-year-blockchain-ai-iot-converge/.

[97] Bild, Leif. "Web 3.0-Convergence of Artificial Intelligence, IoT and Blockchains." Medium. April, 2018. https://medium.com/@lbildoy/web-3-0-convergence-of-artificial-intelligence-iot-and-blockchains-ac3e72c3a1.

[98] Petracek, Nelson. "Is Blockchain The Way To Save IoT?" Forbes. July, 2018. https://www.forbes.com/sites/forbestechcouncil/2018/07/18/is-blockchain-the-way-to-save-iot/#51a1b8805a74.

[99] Mearian, Lucas. "IoT Could Be the Killer App for Blockchain." Computerworld. June, 2018. https://www.computerworld.com/article/3284024/blockchain/iot-could-be-the-killer-app-for-blockchain.html.

[100] Monegro, Joel. "Blockchain IoT Projects and Applications | 2018 Guide." Postscapes. October, 2018. https://www.postscapes.com/blockchains-and-the-internet-of-things/.

[101] "Launching Your Blockchain Project Has Never Been Easier." Enabling the Future of IoT Filament. https://filament.com/.

[102] "The Next Generation of Distributed Ledger Technology." The Next Generation of Distributed Ledger Technology | IOTA. https://www.iota.org/

[103] Marr, Bernard. "Artificial Intelligence And Blockchain: 3 Major Benefits Of Combining These Two Mega-Trends." Forbes. March, 2018. https://www.forbes.com/sites/bernardmarr/2018/03/02/artificial-intelligence-and-blockchain-3-major-benefits-of-combining-these-two-mega-trends/#cdfb2774b44b.

[104] Dinh, Thang, and My Thai. "AI and Blockchain: A Disruptive Integration." Future of AI. September, 2018. http://www.people.vcu.edu/~tndinh/papers/IEEEComp18_Blockchain+AI.pdf.

[105] "We're Making Decentralization Work." Enigma. https://enigma.co/.

[106] "NTU Ranks Top 3 Globally in Citation Impact of AI Research." School of Computer Science and Engineering. May, 2017. http://scse.ntu.edu.sg/NewsnEvents/Pages/News-Detail.aspx?news=065e31ba-12cf-4e5a-92b0-19d9915daf6f.

[107] Lee, Kai-fu. "What China Can Teach the U.S. About Artificial Intelligence." The New York Times. September, 2018. https://www.nytimes.com/2018/09/22/opinion/sunday/ai-china-united-states.html.

[108] Kaia. "5 Reasons Why Singapore Is a Famous Hub for Blockchain and Crypto Conferences." CoinStaker | Bitcoin News. September, 2018. https://www.coinstaker.com/5-reasons-why-singapore-is-a-famous-hub-for-blockchain-and-crypto-conferences/.

[109] "Gartner Says AI Technologies Will Be in Almost Every New Software Product by 2020." Gartner. July, 2017. https://www.gartner.com/en/newsroom/press-releases/2017-07-18-gartner-says-ai-technologies-will-be-in-almost-every-new-software-product-by-2020.

[110] Russell, Kyle. "Algorithmia Launches With More Than 800 Algorithms On Its Marketplace." TechCrunch. March, 2015. https://techcrunch.com/2015/03/12/algorithmia-launches-with-more-than-800-algorithms-on-its-marketplace/.

[111] Houlding, David. "Improve Patient Engagement and Efficiency with AI Powered Chatbots." Blog | Microsoft Azure. September, 2018. https://azure.microsoft.com/en-us/blog/improve-patient-engagement-and-efficiency-with-ai-powered-chatbots/.

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[112] Neubronner, Eugene and Chua, Hian Hou. "Artificial Intelligence Governance and Ethics Initiatives - Infocomm Media Development Authority." Base. June, 2018. https://www.imda.gov.sg/about/newsroom/media-releases/2018/artificial-intelligence-governance-and-ethics-initiatives.

[113] Wheatley, Mike. "Google Researchers Develop a Test for Machine Learning Bias." SiliconANGLE. December, 2016. https://siliconangle.com/2016/12/22/google-researchers-develop-test-machine-learning-bias/.

[114] Gershgorn, Dave. "Facebook Says It Has a Tool to Detect Bias in Its Artificial Intelligence." Quartz. May, 2018. https://qz.com/1268520/facebook-says-it-has-a-tool-to-detect-bias-in-its-artificial-intelligence/.

[115] Knight, Will. "Microsoft Is Creating an Oracle for Catching Biased AI Algorithms." MIT Technology Review. May, 2018. https://www.technologyreview.com/s/611138/microsoft-is-creating-an-oracle-for-catching-biased-ai-algorithms/.

[116] Lomas, Natasha. "IBM Launches Cloud Tool to Detect AI Bias and Explain Automated Decisions." TechCrunch. September, 2018. https://techcrunch.com/2018/09/19/ibm-launches-cloud-tool-to-detect-ai-bias-and-explain-automated-decisions/.

[117] Bennink, Julie. "Accenture Launches New Artificial Intelligence Testing Services." Accenture. February, 2018. https://newsroom.accenture.com/news/accenture-launches-new-artificial-intelligence-testing-services.htm.

[118] "Why, Robot? The Social, Moral and Cultural Implications of AI." The Future Shapers. November, 2017. https://thefutureshapers.com/robot-social-moral-cultural-implications-ai/.

[119] Thomas, Jessica. "Regulatory Complexity Is the Greatest Barrier to Widespread Blockchain Adoption, While Regulatory Changes Are the Primary Driver of Broader Integration, According to EY Poll." Home. June, 2018. https://www.ey.com/en_gl/news/2018/06/regulatory-complexity-is-the-greatest-barrier-to-widespread.

[120] Hankin, Aaron. "Survey Finds a Surprising Barrier to Blockchain Adoption." MarketWatch. August, 2018. https://www.marketwatch.com/story/survey-finds-a-surprising-barrier-to-blockchain-adoption-2018-08-28.

[121] Chen, Zhuling. "Commentary: How Should We Regulate Blockchain? It Depends on Which Country You Ask." Fortune. June, 2018. http://fortune.com/2018/06/25/blockchain-cryptocurrency-technology-regulation-bitcoin-ethereum/.

[122] "2018 Blockchain Regulation Roundtable." Blockchain Research Institute. May, 2018. https://www.blockchainresearchinstitute.org/regulation-roundtable/.

[123] "NUS Forms Academic Blockchain Think Tank." Enterprise Innovation | Asia's Premier Business and Technology Publication. September, 2018. https://www.enterpriseinnovation.net/article/nus-forms-academic-blockchain-think-tank-814997289.

[124] Bowcut, Steven. "The Future of Cybersecurity Is Convergence." Brilliance Security Magazine | Illuminating the Intersection of Physical and Cyber Security. May, 2018. http://brilliancesecuritymagazine.com/guest-contributor/the-future-of-cybersecurity-is-convergence/.

APPENDIX C: WORKGROUP MEMBERS

Prof. Steven Miller (Chairman of Workgroup 4)	Vice Provost (Research), Singapore Management University
Dr. Tan Geok Leng (Co-Chairman of Workgroup 4)	Chief Executive Officer, AIDA Technologies Pte. Ltd.
Mr. Richard Koh	Chief Technology Officer, Microsoft Singapore
Mr. Laurence Liew	Director, AI Singapore
Dr. Rick Goh	Director, Institute of High Performance Computing
Prof. David Lee	Co-Founder, BlockAsset Management Pte. Ltd.
Mr. Leong Der Yao	Director, Government Technology Agency
Dr. Meeta Yadav	Director, IBM Innovation Services Pte. Ltd.
Dr. Simon See	Chief Solution Architect, Nvidia Singapore Development Pte. Ltd.
Mr. Ho Vee Leung	Head of IT, PSA International
Dr. Sinuhe Arroyo	Chief Executive Officer, Taiger Singapore Pte. Ltd.
Dr. Dong Xinshu	Chief Executive Officer, Zilliqa Research Pte. Ltd.
Mr. David Tan	Chief Technology Officer, ST Electronics Pte. Ltd.

Ms. Veronica Tan	Director, Next Generation Platform, Infocomm Media Development Authority
Mr. Koh Wee Siong	Assistant Director, Next Generation Platforms, Infocomm Media Development Authority
Mr. Anthony Yeo	Senior Manager, Next Generation Platforms, Infocomm Media Development Authority
Mr. Peter Lin	Manager, Next Generation Platforms, Infocomm Media Development Authority