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BLOCKCHAIN

Fundamentals and Enterprise Applications

[Full Paper: Parts 1 and 2]

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Preface

For over three decades, the Center for Supply Chain Research® (CSCR®) connects researchers and professionals from leading organizations within a community that is shaping the future of the supply chain discipline. Prolific research engagement with business and industry is fundamental to our mission to be a leader in supply chain knowledge creation and dissemination. A part of the internationally ranked Penn State Smeal College of Business, with over 30 affiliated faculty members from the Department of Supply Chain and Information Systems (SCIS), CSCR® provides industry partners an access to one of the largest and most prestigious academic concentrations of supply chain management research in the United States.

One of CSCR® recent collaborative research initiatives welcome GoChain as our highly regarded partner in the enterprise and government blockchain solutions. This partnership has brought Penn State among an early adopter and one of 50 respected and reputable companies that will help power projects aimed to bring the potential of blockchain to supply chain management. The blockchain deployed by GoChain is a reputation-driven blockchain network wherein Penn State operates as one of signing nodes. GoChain's blockchain operates a fully functioning node with various advantageous features. It leverages the reputation of both the university and its other node signers to validate real business transactions. In doing so, we are an integral part of an operational blockchain that is both very sustainable and highly effective, given its extraordinarily high energy efficiency and high transaction speeds, respectively.

In today's innovation-driven economy, the Smeal college of business is taking a significant step forward under this new partnership to advance groundbreaking research and innovative applications of blockchain technology in supply chains. We have confidence in this partnership that it not only will enable Smeal researchers the opportunity to leverage the game-changing blockchain technology in addressing pivotal research questions with real-world applications, but also foster our industry partners in their endeavor to spur innovation and sharpen competitive advantages.

Given the novelty of the technology, this white paper explores blockchain technology from various perspectives—ranging from a bird-eye view, an evolutionary view, a "light" technical view, to an enterprise applications view. With this white paper, the authors hope to bring researchers and business readers up to speed on the essential foundations about blockchain technology and its state of play in enterprise applications. We hope that interested readers find the information herein a helpful starting point in the journey to bridge the boundaries between the prospects and beneficial realization of this promising technology.

Introduction

Blockchain technology has become an exuberant subject of discussion among researchers and business professionals in recent years. To the mainstream, their acquaintance with blockchain is largely attributed to its early application as the underlying technology of a cryptocurrency Bitcoin. However, the technology has significantly advanced since the introduction of Bitcoin in 2009, bringing with it the potentials for expanding fields of applications. Indeed, many new use cases are envisioned and their development as enterprise solutions is progressing remarkably well. According to Gartner survey of blockchain service providers, 14 percent of enterprise blockchain projects moved into production in 2020, up from only 5 percent in 2019.[1]

Despite its rise to fame, blockchain is still a puzzle box to most business audiences. Its novelty and dynamic innovations contribute to the increased complexities in grasping how blockchain's capabilities are evolving and where such capabilities may be marshalled to empower business value. Convolutions notwithstanding, its disruptive potential means that businesses cannot afford to be negligent towards blockchain. To facilitate business researchers and professionals in getting up to speed on this promising, but yet-to-mature technology, this paper provides a snapshot of blockchain technology capabilities, and how it is being leveraged in businesses, focusing on supply chain management applications.

Given the current complex dynamic of blockchain development, this paper offers a "deep basic" that goes beyond the technology's generic working mechanisms, but without delving heavily into technical particulars. Our paper is developed based on a review of both web-based resources and literature published during a 2016–2021 timeframe, focusing on, but not solely limiting to, managerial and some technical articles. The aim of this paper is to provide a synopsis of background essential to understanding blockchain's evolving capabilities that would provide a foundation for contemplating potential business applications. Accompanying the background synthesis are lists of selected readings for interested audiences wishing to explore further on the subjects.

A Bird's Eye View: The Nuts and Bolts of Blockchains

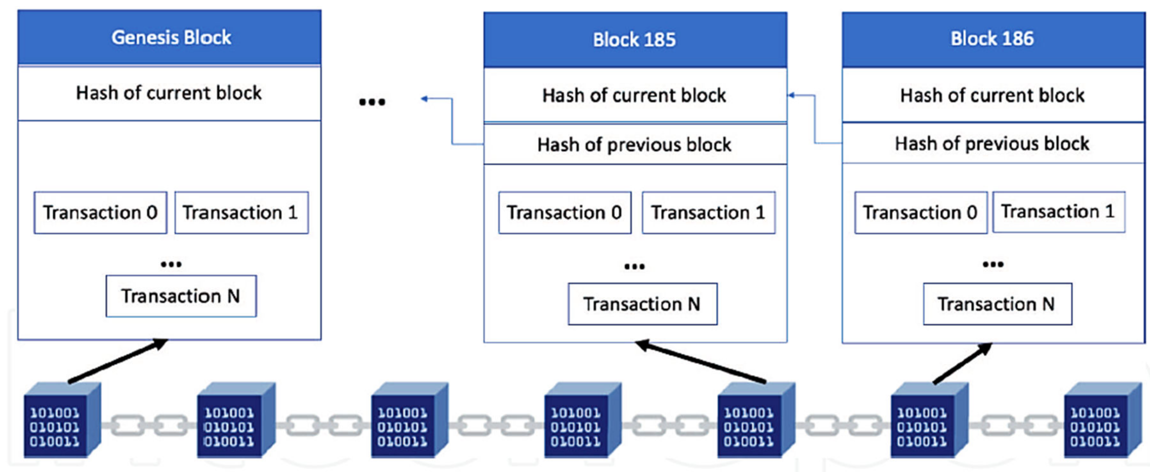
As depicted in Figure 1, a blockchain is a "data structure" consisting of a chain of cryptographically linked units of blocks. Each block contains congregated, mathematically encrypted transaction records. Such data could represent financial transactions, inventory records, food shipment records, parts certifications, sensor data, or any other types of assets that can be prescribed in a digital form. In addition to a set of transaction records from the same time period, each block also contains metadata—

[1] Litan 2021

typically including a time stamp, a unique cryptographic fingerprint known as a "hash" and, except for the first block (called the *genesis block*), the previous block's hash that links the blocks together (thus, a *blockchain*). With the cryptographic hashes and links, the acts of altering individual blocks or inserting a block between two existing blocks are prevented.[2]

Blockchain data structure is "append only" such that old entries are never deleted or modified. Due to the permanency, its chain of blocks lengthens as the string matures, and with it, growing blockchain data that represent a complete historical record of all the transactions that have taken place since the origin of the blockchain.[3] Overall, blockchain data structure not only ensures data integrity and authenticity, but also underpins the traceability feature of blockchain systems.

Figure 1: Blockchain Data Structure



Source: Zhang (2019)

A blockchain system operates as a "shared, distributed digital ledger," with each ledger representing a chain of blocks. Blockchain systems run over the Internet across a distributed peer-to-peer (P2P) network of computers (called *nodes*) as shown in Figure 2. Blockchain networks vary in terms of architectural characteristics, ranging from public/private/consortium to permissioned/permissionless.[4] These designs, whiles essentially providing the same P2P network outcomes, have various application characteristics in which one may be preferred over another. Fundamentally though, all blockchains are,

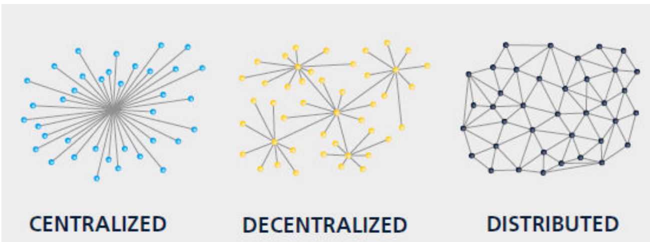
[2] Alicke et al. 2017; Anwar 2019; Boaventura 2018; Bottoni et al. 2020; Brakeville and Perepa 2017, 2019; CAICT & Trusted Blockchain Initiatives 2018; Deloitte 2018; Ganne 2018; ; GEP 2020; Gupta 2020; Hewa, Ylianttila, and Liyanage 2021; IBM n.d.; Ismail and Materwala 2019; MIT CTL 2019; Mobindustry 2020; Murray 2018; NPD 2018; OECD n.d.; Richter 2019; Sabry, Kaittan, and Majeed 2019; Sanka et al. 2021; Sarmah 2018; Trouton, Vitale, and Killmeyer 2016; Voshmgir 2019b; WEF 2019b, 2019d; Zhang 2019

[3] AWS 2020; Brakeville and Perepa 2017; Carson et al. 2018; Cottrill 2018; Gandhi, Majumdar, and Monahan 2018; NPD 2018; PwC 2019; Sanka et al. 2021; Voshmgir 2019b

[4] Boaventura 2018; Carson et al. 2018; DHL 2018; Dutta et al. 2020; Gandhi, Majumdar, and Monahan 2018; Ganne 2018; Iansiti and Lakhani 2017; Montecchi, Plangger, Etter 2019; Schmahl et al. 2019; UCL CBT 2019; Viniak 2019; Voshmgir 2019b; WEF 2019b, 2019d

in one form or another, distributed and the architecture is based more upon the network and application than the function itself. Further elaboration on this subject is provided later on in this paper under the blockchain network architecture section.

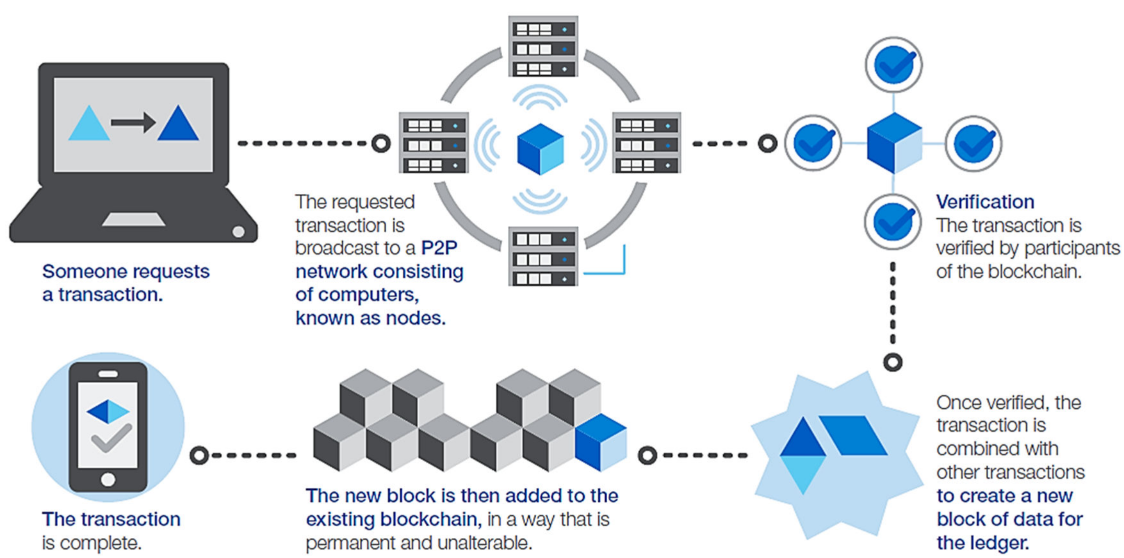
Figure 2: Centralized, Decentralized, and Distributed Network



Source: DHL (2018)

The simplified working mechanisms of blockchain is depicted in Figure 3. In a nutshell, with each new transaction request, the transaction is broadcasted and cryptographically validated by network participants using consensus mechanisms. All validated transactions are time-stamped and bundled into a new block. The new block carrying the time-stamped transaction data and metadata is then added to the pre-existing blocks to form a chronological chain of blocks. Once added, the transaction is deemed complete and the block becomes a permanent part of the ledger.[5]

Figure 3: Simplified Working Mechanism of Blockchains



Source: WEF (2018)

[5] Alicke et al. 2017; Anwar 2019; Boaventura 2018; Bottoni et al. 2020; Brakeville and Perepa 2017, 2019; CAICT & Trusted Blockchain Initiatives 2018; Deloitte 2018; Ganne 2018; IBM n.d.; Ismail and Materwala 2019; Murray 2018; Richter 2019; Sabry, Kaittan, and Majeed 2019; Sanka et al. 2021; Sarmah 2018; Zhang 2019

An Evolutionary View: Generations of Blockchain Technology

While the previously discussed working mechanisms are customary for all blockchains, the technologies on which they are operated are becoming more and more dynamic as blockchain is still a nascent and evolving technology.[6] Despite the lack of consensus on the depictions of blockchain technology evolutions, four generations of blockchain can be discerned from literature as briefly described below.

Blockchain 1.0 – 2009: Cryptocurrency

Cryptocurrencies were the original application of blockchains, with the focus on ensuring correct monetary transactions. This first-gen blockchain began when an unidentified individual or group of individuals under the alias Satoshi Nakamoto published a white paper "Bitcoin: A Peer-to-Peer Electronic Cash System" on October 31, 2008. The first ever Bitcoin transaction took place on January 12, 2009, when *Nakamoto* sent a computer scientist Hal Finney 10 Bitcoins (BTC). Aside from Bitcoin, other examples of blockchain platforms in this generation are Litecoin, Dogecoin, Reddcoin.[7]

Key limitations of Blockchain 1.0 are high energy consumptions to run the mining (creation of the currency) equipment, expensive hardware setups needed to adjust mining rigs, scalability problems, low transaction processing speed and throughput, and relatively small data/block size.[8]

Blockchain 2.0 – 2015: Smart Contracts and Asset Tokenization

The second generation of blockchain distinguishes itself from the predecessor by its expanding functionalities beyond cryptocurrencies. Led by the automation and the development of trusted code platforms like Ethereum and Hyperledger, Blockchain 2.0 introduces the concept of "smart contracts" and made possible the "digital tokenization of physical assets." Together, these technologies support decentralized autonomous organizations (DAOs)—a concept where "decentralized" refers to no need for any central body interventions, and "autonomous" refers to the amplification of smart contracts and encoded transactions on the blockchain.[9]

The concept of smart contracts was introduced in late 2013 by a Russian-Canadian developer, Vitalik Buterin, who published a white paper that proposed a platform combining traditional blockchain functionality with the execution of computer code. In 2014, Buterin put together a project called Ethereum which was later launched in 2015, marking the rise of the second-gen blockchain.[10] Since its

[6] Business APAC 2019; CAICT & Trusted Blockchain Initiatives 2018; Carson et al. 2018; Furlonger and Uzureau 2019

[7] @induction 2021; Barry 2017; Beyer 2018; Boaventura 2018; Built in n.d.; Business APAC 2019; Cummings 2019; Ganne 2018; Heintzman 2019; Iansiti and Lakhani 2017

[8] @induction 2021; Alam 2018; Beyer 2018

[9] Beyer 2018; Bhalla n.d.; Ganne 2018; Heintzman 2019; Nair 2019

[10] Built in n.d.; Business APAC 2019; Cummings 2019; Ganne 2018

first introduction in Ethereum, smart contracts are now a critical component of many platforms and applications being built using blockchain, such as EOS, Cardano, Tron, NEM, Neo, BAT, Stellar, Waves, and HyperLedger Fabric. Different smart contract platforms generally include a set of specific features aimed for particular applications, and may or may not require tokenization. A case in point, Ethereum is mainly developed for the applications which require tokenization.[11]

Tokenization of assets elevates blockchain technology far beyond a record-keeping ledger. Through tokenization—the process of converting the assets and rights or claim to an asset into a digital token in a blockchain network—various types of "value" can be digitally represented, depending on the business requirements. Some examples include bank balances or fiat currency, product inventory, supply chain documents, receipts, authorizations, loyalty points, and subscriptions.[12]

Key limitations of Blockchain 2.0 are problems of scalability, overpower consumption to run the mining equipment, the majority or 51 percent attack, and smart contract code vulnerability.[13]

Blockchain 3.0 – 2018: Enterprise Blockchain

In 2018, blockchain technology began its major breakthrough and adoptions in industries, and by 2019, the year of enterprise blockchain adoption was finally proclaimed.[14] A number of defining features that address the major limitations of the previous generations have moved blockchains into the third generation, particularly the followings:[15]

- **Decentralized applications (dApps).** Third-gen blockchain advanced the distributed application (dApp) capabilities of blockchain. dApps run on top of blockchain infrastructure, typically using smart contracts. For example, the decentralized autonomous organization (DAO) in Ethereum, chaincodes in Hyperledger, and the domain name service (DNS) in Namecoin all use smart contracts to execute.[16]
- **Inter-blockchain.** Also described as blockchain-to-blockchain (BC2BC) and relational blockchain, this feature not only enables the ability to process transactions between different blockchains but also improves expansion capability of the system. Cross-chain communication techniques and technologies such as sidechain and sub-blockchain represents advancement in this area. Briefly described, *sidechains,* also known as pegged sidechains and bespoke blockchains, allow different transactions to perform independently on multiple chains, and can occur in one-way (from one

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[11] @induction 2021; Alam 2018; AWS 2020; Bottoni et al. 2020; Cummings 2019; Hewa, Ylianttila, and Liyanage 2021; Voshmgir 2019a

[12] Arun, Cuomo, and Gaur 2019; Levy 2019; Microsoft 2019

[13] @induction 2021; Alam 2018; Beyer 2018; Cummings 2019

[14] Sanka et al. 2021

[15] Additional examples of blockchain with one or more of the following features are Aion, Banano, Cardano, Cosmos, EOS, Hashgraph, Holochain, IOTA, Lisk, Matrix AI, NANO, NXT, Polkadot, Quarkchain, Ripple, and VeChain (@induction 2021; Anwar 2018, 2019; Beyer 2018; Business APAC 2019; Cummings 2019; Ganne 2018; Heintzman 2019; Reshetchenko 2019).

[16] Heintzman 2019; Ismail and Materwala 2019; Packtpub n.d.; PwC 2018; Sanka et al. 2021

sidechain to another) or two-way (both sides of two sidechains) manners. The *sub-chain* technology is a blockchain with independent functions derived from the mainchain. Significant benefits of these technologies are that they provide some interoperability between blockchains. Any changes made in the data in one blockchain can be immediately updated in another, and that actor of one blockchain can access resources from another blockchain without deliberately joining it. It also eliminates network bottlenecks, and improve the overall throughput, availability, and scalability of the system.[17] Examples of inter-blockchain projects are Aion, Ark, Polkadot, and IBM (connecting two of its own blockchains, namely TradeLens and FoodTrust).[18]

Among key limitations of Blockchain 3.0 are back-end full control over the system integrity and security, and the cost and complexity of implementations.[19]

Blockchain 4.0 [Hypothetical] – 2019: AI-enabled, IoT-converged Blockchain

Blockchain 4.0 is still largely in a hypothetical state where there are different views on what it might look like. A growing consensus can be gauged, however, that the next-gen blockchain would materialize when Blockchain 3.0 converges with artificial intelligence (AI) and Internet of Thing (IoT) technologies.[20] Accordingly, expectations postulated for the next-gen blockchain are: (1) ability to accommodate the Internet of Everything (IOX), and (2) fully AI-based consensus algorithms to replace the presence of humans from certain roles in the blockchain, such as validating transactions and adding the new blocks into the blockchain.[21]

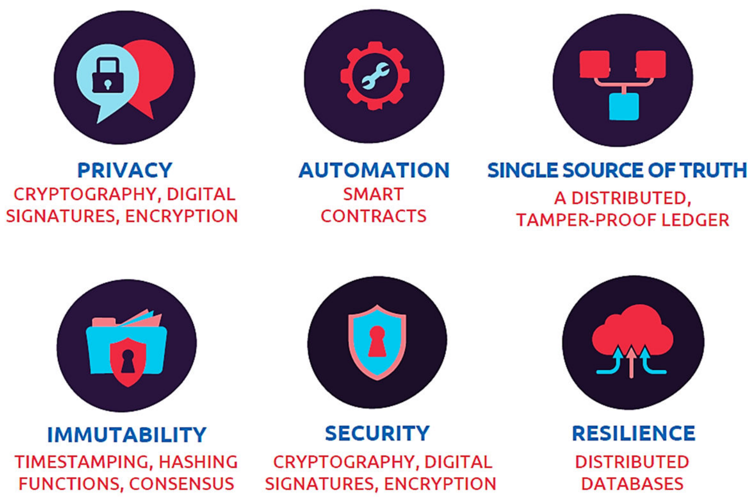
At the time of this writing, developers of blockchain projects such as Aergo, Insolar, Free TON, Propersix, and Relictum Pro have claimed that they are bringing the next-gen blockchain into existence, featuring AI- and/or IoT-enabled blockchain technology.[22]

[17] Anwar 2018; Cummings 2019; CAICT & Trusted Blockchain Initiatives 2018; Deloitte 2016; Nair 2019; Sarmah 2018; WEF 2020; Xia, Grover, and Lieb 2021
[18] Xia, Grover, and Lieb 2021
[19] @induction 2021
[20] Business APAC 2019; Cummings 2019; Deloitte 2016; Nair 2019; PwC 2018; WEF 2018
[21] @induction 2021
[22] @induction 2021; Business APAC 2019; Nair 2019

A "Light" Technical View: Key Concepts and Building Blocks of Blockchain Systems

Behind the foregoing nuts-and-bolts and technological evolution narrations are a number of key concepts and building blocks that warrant further elaborations. These "deep basics" are essential to pave a foundation for understanding key attributes of blockchain, depicted in Figure 4, as well as its capabilities and potential enterprise applications.

Figure 4: Key Advantageous Attributes of Blockchain Technology



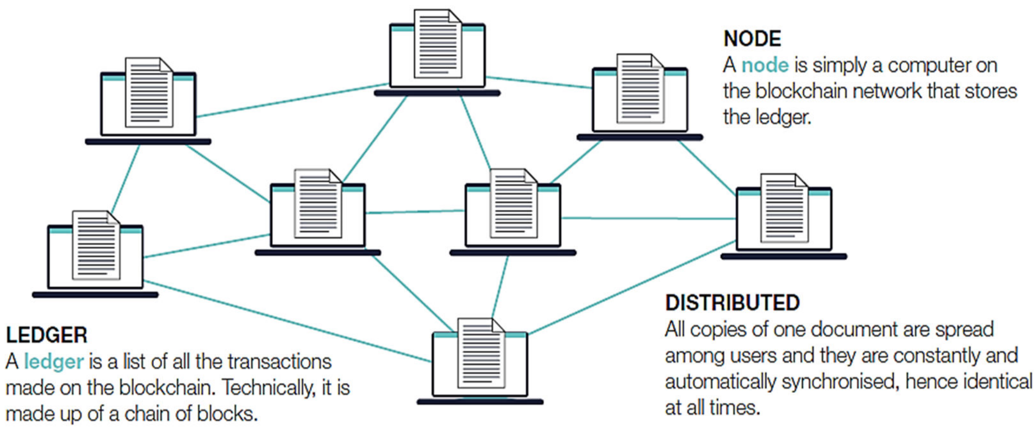
Source: de Chillaz et al. (2021)

Peer-to-Peer (P2P) Network

Peer-to-peer (P2P) architecture is at the core of blockchain systems. It consists of a group of devices (called nodes) that are connected together to create a distributed network of users that individually participate in the network by replicating, validating, and saving a copy of the ledger. As shown in Figure 5, each node in a P2P blockchain network holds a copy of the ledger that contains a complete, identical record of all the transactions ever recorded in that ledger. Each node also acts as an individual peer that can communicate and do transactions *directly* with the others without having to record or process the transactions through intermediaries or a central authority. As such, blockchain-based ledgers are inherently "distributed" and "redundant" in nature since there is no central administrator or central data storage, and the same ledger of transactions is replicated and synchronized across multiple different nodes in the network.[23]

[23] 101 Blockchains 2020; Anwar 2019; Bender, Burchardi, and Shepherd 2019; Berke 2017; Binance Academy n.d.; Brakeville and Perepa 2017; Gartner 2019; Gupta 2020; Iansiti and Lakhani 2017; Ismail and Materwala 2019;

Figure 5: A Peer-to-Peer Blockchain Network



Source: OECD (n.d.)

The P2P architecture renders blockchain to be resilient and reliable. Due to the distributed and redundant dispositions, there is no single point of failure or attack and if a participant leaves the network, none of the data posted by that node on the blockchain will be lost.[24] It is acknowledged, however, that the P2P architecture is not unique to blockchain, as it is also leveraged in other distributed computing applications, such as web search engines, streaming platforms, online marketplaces, and the InterPlanetary File System (IPFS) web protocol.[25]

Cryptography

Cryptography is key to enable various systemic attributes of blockchain security and to ensure verifiability of transactions for authenticity and integrity.[26] **Hash functions** are one of the most extensively used cryptographic algorithms in blockchain technology. In a nutshell, a hash algorithm is a mathematical function that turns any input (e.g., password or jpeg file) into a fixed size output called a hash.[27] Hash functions have two essential properties—first, the hash function is relatively easy to compute; and second if the input data change even slightly, the hash function value changes in an unpredictable way.[28]

Given the two properties, hash functions underpin blockchain's information security, serving the dual purpose of *identification* and *integrity verification.* With a hash providing a unique digital fingerprint of the data, blocks in a blockchain can be identified by their hash and linked together in the chain so that

Mobindustry 2020; OECD n.d.; Sanka et al. 2021; Seibold and Samman 2016; Thompson and Albright 2019; UCL CBT 2019; Viniak 2019; WEF 2019d

[24] Enthoven et al. 2020; Ganne 2018; Küpper 2019; Sarmah 2018; UCL CBT 2019; WEF 2019d

[25] Binance Academy n.d.

[26] Arun, Cuomo, and Gaur 2019; AWS 2020; Brakeville and Perepa 2019

[27] Poston 2020

[28] MIT CTL 2019; Tasca and Tessone 2019

a blockchain retains the complete history of transactions executed since the very first one.[29] In the latter purpose, hash functions enable authentication for blockchain transactions and blocks. Because any change in any part of the data will result in a completely different hash, network participants can verify that a block of data has not been tampered with by checking the hash of the data against the previously computed and stored hash value for that data.[30]

Another important cryptography used in blockchain technology is asymmetric key algorithms that fall under the category of public-key cryptography. **Asymmetric key cryptography** involves two keys, namely public and private keys, that work in tandem for encryption, decryption, and digital signatures. For a start, transactions occur between blockchain addresses, which are derived by a process of hashing public keys.[31] Thus, using public keys, the sender can transmit encrypted information securely. Private keys are required to decrypt the encrypted information, and only the intended recipients can do so with their own unique private key.[32] For signatures, hash functions described earlier are a vital part of digital signature algorithms.[33] To digitally signed on a blockchain, the user first hashes the transaction data to be signed using a hash function. The hashed data is then encrypted, using the user's private key to provide user authentication. The resulting encrypted output is known as the digital signature of that transaction.[34] Overall, asymmetric key cryptography enables transacting parties to interact privately over the Internet, authenticate their identity, and verify blockchain data.[35]

Blockchain Network Architecture

The architectural variations of blockchain platforms are expanding as the number of applications increases. In a broad sense, blockchain network architecture can be classified based on two factors, namely node access control and governing entity, as summarized below:

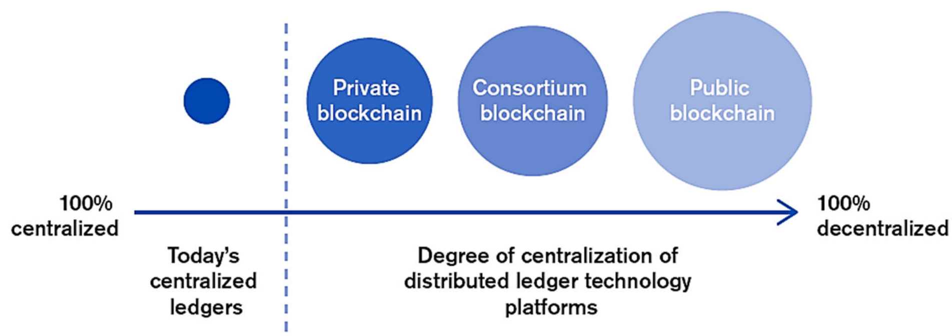
- **Node access control: Permissioned (Closed) and Permissionless (Open).** Depending on whether a network has rules regarding permissions for users to access to or use blockchain resources, blockchain platforms can be classified into "permissioned" and "permissionless" blockchains. A permissionless or *open* blockchain is one that is open to anyone with a computer to participate, allowing all nodes an access with no restrictions imposed on who can contribute to the update and management of the ledger. In contrast, a permissioned or *closed* blockchain places restrictions on who is allowed to access the network which usually requires some form of authorization by a central

[29] Deloitte 2016; Hewa, Ylianttila, and Liyanage 2021; Poston 2020; WEF 2019b
[30] Chow 2016; Euromoney n.d.a; MIT CTL 2019; Poston 2020; WEF 2019b
[31] Berke 2017; Chow 2016
[32] Anwar 2019; Ganne 2018; MIT CTL 2019; Sanka et al. 2021
[33] Poston 2020, WEF 2019b
[34] Chow 2016; Ismail and Materwala 2019
[35] MIT CTL 2019

authority, and there can also be various levels of accessibility to and control of data granted to different participants.[36]

- **Governing entity: Public, Private, and Consortium/Federated.** The distinction between public, consortium, and private blockchains lies in the governing entity who manages and controls the platform. In a public blockchain, no specific entity governs the platform; whereas in a private and consortium or federated platform, a single entity and a group of entities, respectively, perform various governing roles. Thus, these different platforms exhibit a different degree of decentralization as illustrated in Figure 6. The least decentralized of the three types, a private platform has a single entity that is highly trusted by the other users governing over which users can access, validate, and write data onto the blockchain. A fully private platform is mostly used in an organization where only a few members are participants of the blockchain network. It is best suited for enterprises and businesses that want to use blockchain only for internal purposes. Consortium blockchains, often used by industry initiatives, have a pre-selected group of members who share the governing responsibilities. They are sometimes described as partially decentralized and semi-private platforms.[37]

Figure 6: Varying Degree of Decentralization across Blockchain Platforms



Source: Ganne (2018)

Due largely to the fact that most public blockchains are permissionless and most private blockchains are permissioned, many literatures use the terms public and permissionless blockchains interchangeably, and similarly for the terms private and permissioned blockchains. In reality, however, some private, and by extension, consortium blockchains can be permissionless. A consortium blockchain FastTrackTrade, for instance, are opened to anyone interested in participating. Meanwhile, some public blockchains can also be permissioned. A public blockchain Ripple, for example, allows "read" access for all users, but "write" access and/or "consensus management" require permission by a preselected set of nodes. In a similar vein, some private or consortium blockchains have a "public interface" for certain permissionless

[36] Boaventura 2018; CAICT & Trusted Blockchain Initiatives 2018; Cottrill 2018; Ganne 2018; IBM n.d.; Schmeiss et al. 2019; Tasca and Tessone 2019

[37] Arun, Cuomo, and Gaur 2019; Banerjee 2019; Ganne 2018; IBM n.d.; Nayyar and Kasthuri 2021; Tasca and Tessone 2019

accessibilities but maintain others as permissioned.[38] Key characteristics of these varying blockchain architectures are highlighted in Table 1.

Table 1: Key Characteristics of Different Blockchain Architecture

Degree of centralization	Public		Consortium		Private
Management	No centralized management		Multiple organizations		Single entity
Access	**Permissionless**	**Permissioned**	**Permissioned**	**Permissionless**	**Permissioned**
	Open read/open validation of transactions	Open read/permissioned validation of transactions	Permissioned OR open read/permissioned validation of transactions	Open read/open validation of transactions	Permissioned read/ validation of transactions
Participants	Anonymous/ pseudonymous	Anonymous/ pseudonymous	Identified	Usually identified	Identified
Validation based on consensus protocol	Open to every participant in the network	Open to every participant in the network, subject to certain conditions	By pre-approved participants (across the organizations involved)	Depending on the consensus protocol chosen for the platform	By pre-approved participants (within the single entity)
Speed of validation	Slow	Quicker	Quick	Quick	Quick
Users' level of privacy	None	None	Tailored to the needs of participants	Tailored to the needs of participants	Tailored to the needs of participants
Computing power required (energy consumption)	High (but variable depending on the consensus mechanism)	Intermediate. Variable depending on the consensus mechanism	Lower	Lower	Lower
Transaction fees	Yes	Yes	Optional – depending on the rules of the blockchain	Optional – depending on the rules of the blockchain	Optional – depending on the rules of the blockchain
Scalability	Low	Slightly higher	Higher	Higher	Higher
Example(s)	Proof of Work (Bitcoin, Ethereum)	Proof of Stake (Nxt)	Blockchains built on Hyperledger Fabric. Permissioned blockchains built on Ethereum.	FastTrackTrade	Private blockchains built on Ethereum

Source: Ganne (2018)

Consensus Mechanisms

The distributed nature of blockchain networks requires untrusted independent participants to reach an agreement on the order and correctness of the set of transactions that constitute a block. A method by which agreements are achieved in blockchain is called consensus mechanisms. They are central not only in confirming data authenticity and keeping the ledger consistently synchronized, but also in ensuring the proper execution of operations inside the blockchain network.[39]

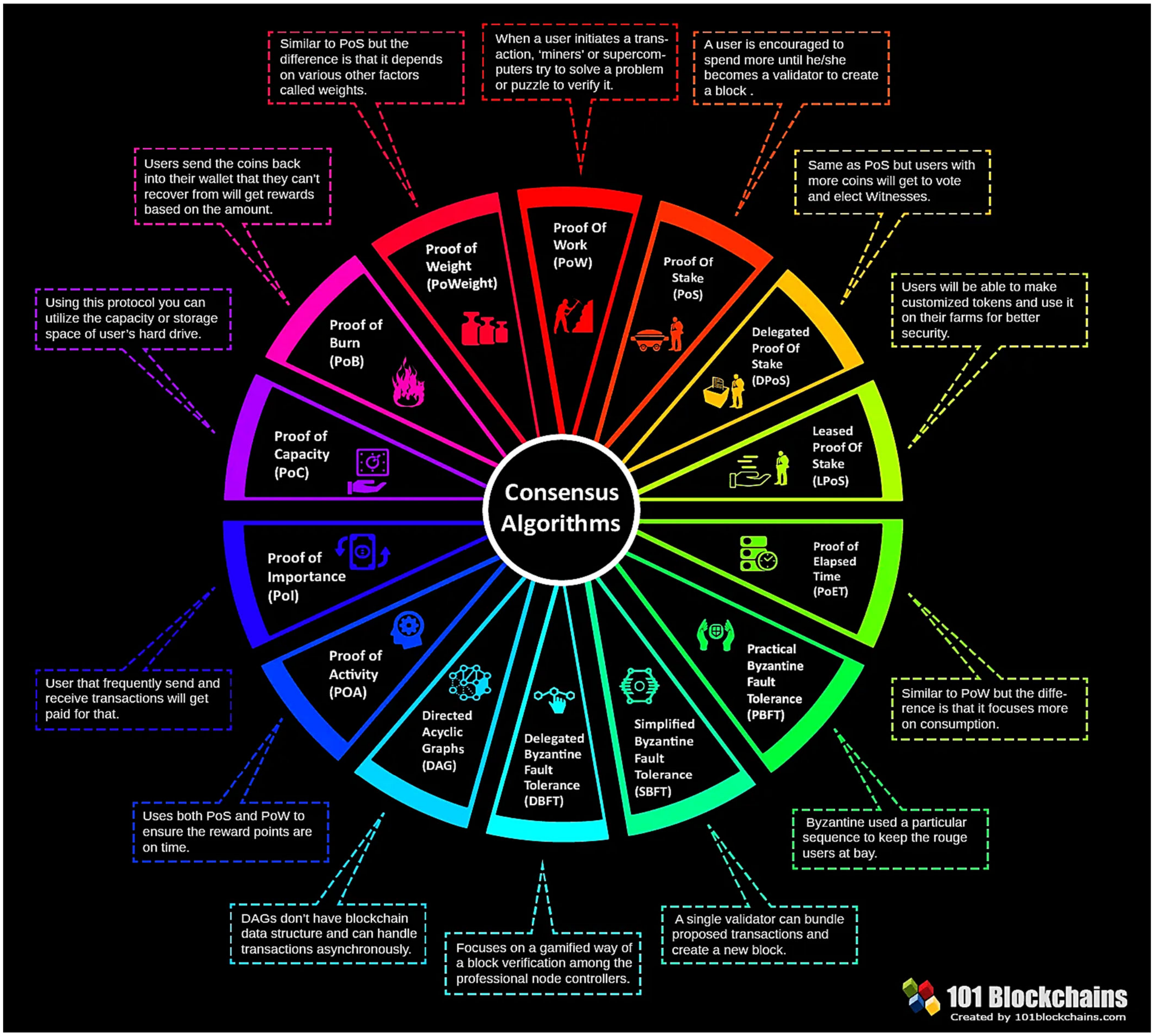
A wide variety of consensus mechanisms have been devised for the aforementioned purposes, each bringing different advantages and disadvantages based on various design concepts—such as transaction speed, energy efficiency, scalability, liveness, fault tolerance, and tamper resistance. Choices of consensus mechanisms, thus, directly impact computational costs and the investment required for

38 IBM n.d.; Ganne 2018; Packtpub n.d.

39 Anwar 2019; Boaventura 2018; Bottoni et al. 2020; Brakeville and Perepa 2017; Gartner 2019; Hyperledger 2017; Litke, Anagnostopoulos, and Varvarigou 2019; MIT CTL 2019; Seibold and Samman 2016; Tasca and Tessone 2019; Zhang 2019

blockchain-based systems.[40] Figure 7 exhibits various types of consensus algorithms, the two most widely used of which, namely proof of work (PoW) and proof of stake (PoS), are briefly described below. However, it is noted that different blockchains using the same general consensus mechanism might have different specifications.[41]

Figure 7: Different Types of Blockchain Consensus Algorithms



Source: Anwar (2018)

[40] Arun, Cuomo, and Gaur 2019; Brakeville and Perepa 2017; Jalal, Shukur, and Bakar 2020; Seibold and Samman 2016; Tasca and Tessone 2019

[41] Voshmgir 2019a

NOTE: Additional examples of consensus algorithms not shown in the figure are: (1) **Proof of Contribution** which combines the concepts of PoW and PoS; (2) **Proof of Authority** which is a modified version of PoS, replacing shares in the network with identity (e.g., VeChain); (3) **Proof of Reputation** which is a variation of Proof-of-Authority model, replacing an authorized identity with a reputed organization as validator (e.g., Gochain, Menlo); (4) **Proof of Space and Proof of Storage** which share the idea of "space as resource" as Proof of Capacity; (5) **Federated Byzantine Agreement** which is another variant of the BFT consensus model (e.g., Ripple); and (6) **Tindermint** (e.g., Cosmos).[42]

- **Proof of work (PoW).** Proof of work is the first blockchain algorithm introduced in the blockchain network, and is used in Bitcoin blockchain. The individual nodes called miners perform a PoW process called mining, which involves solving complicated mathematical puzzles. The puzzles can only be solved with trial and error. Hence, miners require extensive computational power for finding solutions quickly. After solving mathematical puzzles, miners receive bitcoins and a small transaction fee, as well as a block as a reward if they are the first one to find the solution. The main flaws of the PoW are intensive computing resource and energy consumption, centralization of miners/mining power, and the 51 percent attack (meaning a possible control of majority users that take over most of the mining power).[43]
- **Proof of Stake (PoS).** In PoS, the network selects an individual node who would act as a validator based on their proportional stake in the network. Thus, instead of investing in expensive computer equipment in a race to mine blocks as in the case of PoW, a validator invests in the coins of the system. Notable examples of blockchains that use PoS are Ethereum, PIVX, NavCoin, Stratis, Peercoin, NEO, and WAVES.[44] Compared to PoW, PoS consensus algorithm is much more energy efficient and less vulnerable to the threat of a 51 percent attack. However, since only a handful of nodes get to participate in the staking on the network, individuals with the most coins could eventually control most of the system.[45]

Tokenization

Tokenization for a blockchain network is the process of converting anything of "value" into a digital representation or a *token*. Transactions and other interactions in a token-based blockchain involve the secure exchange of value that comes in the form of these digital tokens. In other words, while blockchain provides the technology that facilitates exchange, ownership, and trust in the network; it is the digital representation of value where tokenization is essential.[46]

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[42] Bosch n.d.; Ganne 2018; Ismail and Materwala 2019; Jalal, Shukur, and Bakar 2020; Joshi 2019; Sanka et al. 2021; Tasca and Tessone 2019; Voshmgir 2019a; Zheng et al. 2017
[43] Anwar 2018, 2019; Boaventura 2018; Deloitte 2016; Joshi 2019; Tasca and Tessone 2019
[44] Anwar 2018; Boaventura 2018; PwC 2018
[45] Anwar 2018; Boaventura 2018; Joshi 2019
[46] Arun, Cuomo, and Gaur 2019; CoreLedger 2019; Iredale 2021; Levy 2019; Microsoft 2019; Subbaraman and Krishnan 2021; Tasca and Tessone 2019; WEF 2019b

Tokens on blockchains can be native to the blockchains (known as a **native token** or **crypto asset**), or a digital representation of an off-chain physical assets (known as **tokenized asset**).[47] These two types of tokens can be further distinguished from the "fungibility" perspective as summarized in Table 2.

Table 2: Fundamental Properties of Tokens on Blockchain from Fungibility Perspective

Fungible Tokens	Non-Fungible Tokens
Identical Tokens of the same type are identical to another of the same type. They have identical specifications.	**Unique** Each token is unique and differs from another token of the same type. They have unique information and attributes.
Interchangeable A token can be interchanged for another with the same value. A 20 EUR bill can be replaced with a combination of other bills and coins that amount to the same value.	**Non-interchangeable** NFTs cannot be replaced with tokens of the same type as they represent unique values or access rights.
Divisible Fungible assets are divisible into smaller amounts. It is irrelevant which and how many units you use, as long as it adds up to the same value.	**Non-divisible** Tokens that are tied to one's identity, like certificates and degrees, are not divisible. It does not make sense to have a fraction of a degree, and they are not interchangeable either.

Source: Voshmgir (2019c)

Native tokens are "fungible" tokens that possess the same characteristics as a real-world currency, and are used in blockchain as a medium of exchange or a protocol-driven exchange mechanism.[48] In an enterprise setting, native tokens are normally minted based on the possession or proof of possession of an asset. Facebook's Libra, for example, is backed by established government-backed currencies and securities.[49] Once minted, these *asset-backed tokens*, called *stable coins*, can be assigned, transferred, redeemed, used as payment, or taken on or off circulation, depending on their use cases. Uses of stable coins help to optimize business processes by eliminating intermediaries and escrow accounts, allowing the settlement to happen alongside the business transaction.[50] Tokens that are built to certain standards can be traded in multiple networks. Currently, ERC-20, where ERC refers to Ethereum Request for Comment, is a well-known fungible tokens standard defined by Ethereum.[51]

[47] Levy 2019; WEF 2019b
[48] Arun, Cuomo, and Gaur 2019; Iredale 2021
[49] Bloomberg News 2019
[50] Subbaraman and Krishnan 2021
[51] Iredale 2021; Subbaraman and Krishnan 2021

Tokenized assets are "non-fungible" tokens (NFTs) that extend blockchain applications far beyond financial services. Through tokenization of physical assets, a digital twin of that asset is represented in a blockchain network. The economic value of the underlying asset is conferred to the NFT and the ownership of that asset is represented by the ownership of the NFT on the blockchain. These properties make it possible to use NFTs to, for example, track and exchange supply chain documentation, manage land registries, manage health records, conduct trades, track and manage movements of goods, and execute smart contracts of IoT devices.[52] Currently, the most popular standard in which NFTs are created is ERC-721 running on Ethereum. These tokens have an advantage in terms of compatibility with other blockchain networks such as EOS and NEO, allowing them to be transacted across these compatible blockchains.[53]

Smart Contracts

A smart contract or crypto contract is a term used to describe *pieces of code* that sit within an individual block on a blockchain ledger, with the software coding such rules being replicated and executed by all the nodes of the blockchain P2P network. The code is an integration of an immutable *set of conditions and corresponding actions* that once triggered—that is when a party initiates a transaction by indicating that predetermined conditions are fully met—will *self-execute* the corresponding actions. If no such transaction has been initiated, the code will not take any steps.[54]

As depicted in Figure 8, smart contract applications have evolved significantly from protocol smart contracts, to scriptable smart contract (revolutionized by Ethereum in 2015), and to the current evolution of "off-chain" connected scriptable smart contracts. It is noted that since smart contracts can reference only information on the blockchain, the current evolution of smart contracts is achieved through oracles. Oracles are a data feed provided by a third-party service provider who acts as an agent for collecting information from outside the network, thus making it possible for smart contracts to interact with data outside of the blockchain environment.[55]

The advancement notwithstanding, it is important to emphasize that smart contracts are essentially a *new means* to business process automation wherein business rules are translated into software. Despite the term "smart" in its name, smart contracts do not have learning capabilities, thus should not be seen as intelligent tools. Rather, they are *rule-based,* self-executing business automation applications that functions according to predetermined conditions and criteria in such a same way as a computer executing on "if x event happens, then execute y action" logic, or conditional programming.[56]

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[52] Arun, Cuomo, and Gaur 2019; CoreLedger 2019; Evans et al. 2016; Iredale 2021; Subbaraman and Krishnan 2021; Tasca and Tessone 2019; WEF 2019b

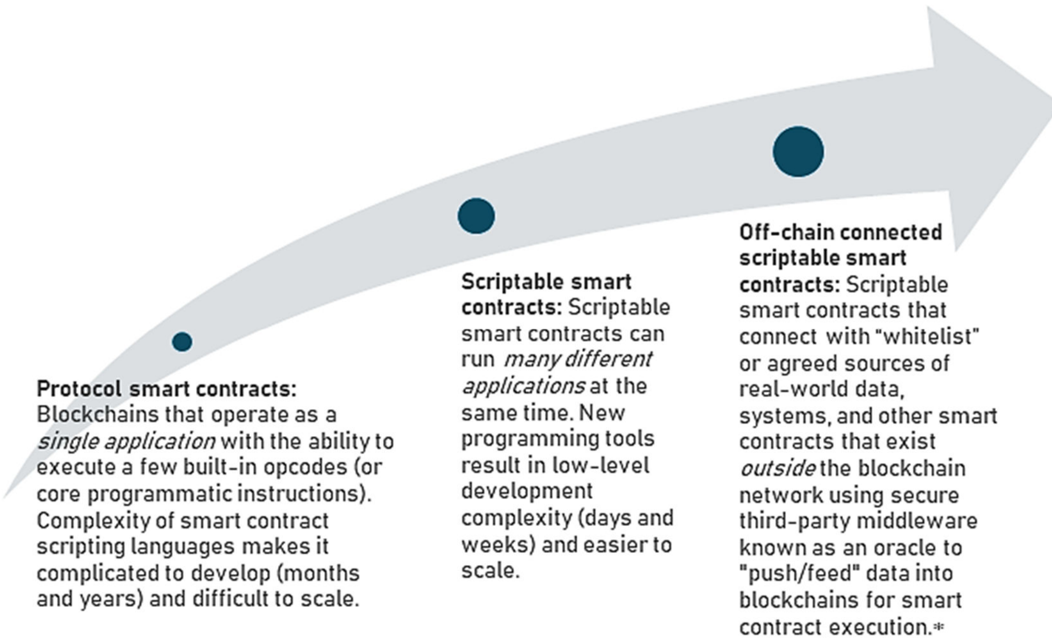
[53] Iredale 2021; Nextrope n.d.

[54] Alam 2018; Blockchain App Factory 2021; Block Key Capital 2018; Bottoni et al. 2020; Information Age 2019; Levi and Lipton 2018; Mearian 2019

[55] Anwar 2019; Ganne 2018

[56] Campbell and Omietański 2018; ChainLink Research 2020; Gopie 2018; Levi and Lipton 2018; Mearian 2019; Stawitz 2019

Figure 8: Evolution of Smart Contract Applications



* Oracles can be hardware-based (e.g., an RFID sensor in a cargo container transmitting location data) or software-based (e.g., information feeds through application programming interface [API]).

Source: ChainLink Research (2020), Levi and Lipton (2018), Mearian (2019), Stawitz (2019)

A Technical Recap: Clarifying Blockchain Misconceptions

Given the heretofore discussions, a number of common misconceptions and myths regarding blockchains are highlighted and clarified in Table 3.

Table 3: Clarifying Common Blockchain Misconceptions

Misconceptions	Clarifications
Blockchain is Bitcoin.	**Blockchain is not Bitcoin.** Blockchain is the technology that underpins Bitcoin, the first application of blockchain technology. However, Bitcoin is just one of several blockchain systems that has found many uses well beyond cryptocurrency.[57]

[57] MIT CTL 2019; NPD 2018; *Supply Chain Navigator* 2020

Misconceptions	Clarifications
Blockchain and distributed ledger technology (DLT) are one and the same.	**Blockchain and DLT are not synonymous.** The terms blockchain and DLT are often used interchangeably. However, while blockchain is a type of DLT, it has distinguishing features from the other types of DLT like Hashgraph, Directed Acyclic Graph (DAG), Holochain, and Tempo (Radix). Blockchain uniqueness lies in the uses of cryptographic and algorithmic approaches to create and verify a continuously expanding, append-only chain of transaction “blocks” that serve the role of a ledger. In other words, blockchain is a DLT, but not all DLTs are blockchains.[58]
Blockchain is an alternative database.	**Blockchain is not a database.** Blockchain is not a database in the traditional sense of databases used in enterprise IT. Blockchain ledgers cannot be read, written, deleted or changed as a formal database can. Nor is it designed for efficient, rapid storage and retrieval of structured data like a database is. Its encrypted chain-like data structure generally makes it slower and more expensive to store and access data than doing so in a standard proprietary database.[59]
Immutable data ensure accurate data.	**Blockchain data immutability is not equivalent to data accuracy.** Blockchain data structure ensure that once data are committed to the ledger, they can neither be tampered with nor removed from the ledger. This data immutability, while warrants the integrity of data, does not guarantee that the data recorded are accurate. The “garbage in, garbage out” philosophy still applies to blockchain.[60]
All blockchains are decentralized.	**Blockchain is distributed, but not always decentralized.** While blockchain’s P2P network structure makes the system inherently distributed, not all blockchains are decentralized. Blockchain networks vary along the centralization and decentralization continuum, depending on the design of the blockchain architecture as to who dictates the rules and controls the ledger and node. In general, permissioned and private blockchains are more centralized than permissionless and public counterparts.[61]

[58] Geroni 2020; UCL CBT 2019)
[59] Abt 2019; Enthoven et al. 2020; Gartner 2019; Gaur and Gaiha 2020; MIT CTL 2019
[60] Enthoven et al. 2020; Kramer 2020; NPD 2018; Stinnes 2019; WEF 2019d
[61] 101 Blockchains 2020; Binance Academy n.d.; Furlonger and Uzureau 2019; Halaburda and Mueller-Bloch 2019; Levy 2019; MIT CTL 2019; Mobindustry 2020; Nayyar and Kasthuri 2021

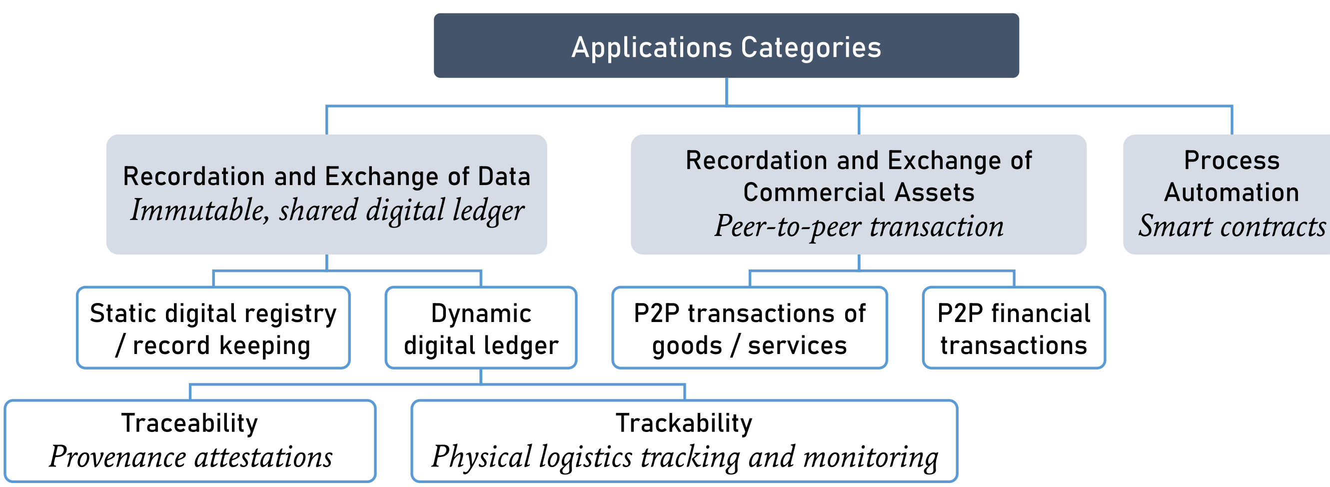
An Enterprise Application View: Blockchain Use Case Taxonomy in Supply Chain

Blockchain for business applications are most favorable in circumstances that are in character with the technology's principal advantages—lack of central hub, low-friction distribution of data, the transparency of a distributed ledger, and the cryptographic security of an immutable, traceable, and auditable data.[62] To put it another way, blockchain could be an applicable solution when the following conditions exist:[63]

- Intermediaries add more complexity than value.
- There is a need for a shared common data stream as a *single source of truth*.
- There are multiple parties involved in sharing and updating data.
- Multiple parties involved have incongruous incentives and/or lack in trust towards one another.
- Transactions are interactive and the interactions among multiple parties are time sensitive.
- There is a need for a permanent, immutable log of records.
- There is a requirement for auditability and/or verification.

In today's complex supply chain ecosystem, these conditions commonly present in all business organizations that now operate in not just one, but multiple supply chains where visibility, transparency, and regulatory scrutiny are becoming more challenging issues. In this paper, blockchain applications in supply chain management are presented in relation to the use case taxonomy framework depicted in Figure 9. The framework distinguishes three core application categories—namely recordation and exchange of data, recordation and exchange of commercial assets, and process automation—each of which is further discussed in this section.

Figure 9: Blockchain Applications Taxonomy Framework



[62] Enthoven et al. 2020; Scribani 2018
[63] Banker 2018a; CAICT & Trusted Blockchain Initiatives 2018; DHL 2018; McBeath 2018; PwC 2019

Recordation and Exchange of Data: Static Digital Registry and Dynamic Digital Ledger

This application category focuses on blockchain capabilities to create records of digital representations of assets and all historical transactions carried out among a network of peers in order to provide a trusted single version of truth. It capitalizes on blockchain benefits of immutable data that easily verified, audited, and accessed by all parties without third-party intermediaries. Use cases in this category do not involve exchange of digital assets on blockchain.[64] Rather their primary intent is to facilitate efficient and frictionless information sharing, enhance data transparency and traceability; while simultaneously ensure data integrity and reduce risks of fraud and malicious transactions.[65] Overall, these capabilities pave the foundation for two brackets of use cases.

Static Digital Registry/Record Keeping

Identity and credentials documents—such as ID cards, professional certificates, patent/IP rights, sustainability credentials, and product/part serial numbers—can be digitalized, fed and stored securely on a blockchain. Static registry can be further enhanced by using NFTs, allowing the transfers of NFTs to be digitally tracked and recorded. Overall, static registry applications enable identity management and support verification of related data. Specific examples of use cases are:[66]

- **Workforce identity management and verification** (e.g., a truck driver's identity, licensing, insurance, safety and performance records, and credit history). Example: Coca-Cola's registry for workers and their contracts using blockchain's validation and digital notary capabilities.
- **Customer information** (e.g., loyalty and rewards, customer identification)
- **Audits and compliance record keeping** (e.g., Know Your Customer [KYC] and/or Know Your Supplier [KYS] audits; ledger for collection and verification of ESG – environmental, social, and governance – data; inspection certificates on aircraft parts required by US Federal Aviation Administration)
- **Proof of claims** (e.g., Fairtrade, conflict-free, non-GMO, and organic certifications)
- **Proof of ownerships** (e.g., IP/copyrights, vehicle registration, digital 3D-printing designs and rights to make 3D printed copies)

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[64] CAICT & Trusted Blockchain Initiatives 2018

[65] 101 Blockchains 2020; Arun, Cuomo, and Gaur 2019; Banker 2018a; Bender, Burchardi, and Shepherd 2019; Carson et al. 2018; Clark 2018; Cognizant 2019, 2020; de Chillaz et al. 2021; Deloitte 2016; DHL 2018; Enthoven et al. 2020; Gandhi, Majumdar, and Monahan 2018; Ganne 2018; Gupta 2020; Herweijer and Swanborough 2018; Iansiti and Lakhani 2017; Kramer 2020; Küpper 2019; Lee 2019; Litke, Anagnostopoulos, and Varvarigou 2019; PwC 2018; Renner, Fedder and Upadhyaya 2018; Sanka et al. 2021; Sarmah 2018; Tasca and Tessone 2019; UCL CBT 2019; Van Hoek et al. 2020; WEF 2019d

[66] AWS 2020; Bender, Burchardi, and Shepherd 2019; Blockchain App Factory 2021; Carson et al. 2018; Chavez-Dreyfuss 2018; Chu and Schatsky 2016; Cottrill 2018; DHL 2018; Deloitte 2018; Dutta et al. 2020; Fedder, Renner, and Upadhyaya 2018; Gandhi, Majumdar, and Monahan 2018; Ganeriwalla et al. 2018; Ganne 2018; Gaur and Gaiha 2020; HDT Trucking Info 2018; Küpper 2019; MIT CTL 2019; Montecchi, Plangger, Etter 2019; NPD 2018; PwC 2018; RSK Labs n.d.; Sanka et al. 2021; Swanson 2017; Toczauer 2019; Trouton, Vitale, and Killmeyer 2016; UCL CBT 2019; Voshmgir 2019c

- **Registry of tokenized carbon offsets**
- **Digital twin data management.** Examples: Groupe Renault for digital twins of vehicles; TÜV Rheinland for digital twins of vehicles
- **Supply chain trade documentation** (e.g., bill of lading, letter of credit, invoices, insurance, border security documentation, tax compliance, phytosanitary inspections). Examples: Cargo Community Network (CCN) for air cargo industry, Mobility Open Blockchain Initiative (MOBI) for automotive industry, TradeLens for global shipping industry
- **Additive manufacturing data management** (e.g., securing and organizing the data generated across the end-to-end AM process)

Dynamic Digital Ledger

Dynamic digital ledger applications are distinguished from the static digital registry by the use of digital identity and data capture technologies (e.g., RFID chips, QR codes, barcodes, IoT sensors, geofencing, near-field communication) in conjunction with blockchain ledger. Such combinations are critical to render near real-time monitoring and updates on supply chain "events" that enhanced traceability and trackability capabilities, as well as end-to-end supply chain transparency.[67]

As in the case of the static registry applications, NFTs may be employed and additional information and context may be added for the metadata in asset tokenization process.[68] In an NFT-based blockchain, where a token code is tied to a blockchain address, when a physical item is tracked with an NFT and is exchanged between counterparties, the NFT will also transfer to the new owner. The inherent immutability of blockchain allows the NFT to include a trusted, complete history of the various transfers of ownership of the items, providing an unbroken chain of visibility of where the item moved through the supply chain. To verify authenticity or chain of custody, one needs simply to read the NFTs' codes and follow their movement from address to address. Taking a step further, unique identifiers such as QR tags, RFID tags or DNA marking of the product itself can be connected with the NFTs and attached to the product, allowing consumers to access data simply by scanning the tags.[69]

Markedly, it is this particular application category that is gaining rapid momentum across various industries, notably in use cases pertaining to tracking and tracing. Track-and-trace capabilities enhanced by blockchain, in turn, enable more effective and efficient supply chain operations for anti-counterfeiting, sustainability, recall and return management, and regulatory compliance and reporting, to name a few. Example use cases are as follows:[70]

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[67] Cognizant 2019; Enthoven et al. 2020; Hammoud et al. 2019; Microsoft 2018; Renner, Fedder and Upadhyaya 2018; UCL CBT 2019; WEF 2019d

[68] Iredale 2021

[69] APQC 2020; AWS 2020; Pradhan et al. 2018; UCL CBT 2019; Vadgama and Tasca 2021; Van Hoek et al. 2020

[70] Bender, Burchardi, and Shepherd 2019; Camerinelli 2018; Chu and Schatsky 2016; Cottrill 2018; de Chillaz et al. 2021; DHL 2018; Dutta et al. 2020; Enthoven et al. 2020; Ganeriwalla et al. 2018; Gandhi, Majumdar, and Monahan 2018; Ganne 2018; Kramer 2020; LaneAxis 2018; Mahamuni 2019; McBeath 2018; Microsoft 2018, 2019; MIT CTL 2019;

- **Traceability: Provenance attestations** (e.g., proof of authenticity, proof of origin, proof of quality, proof of integrity, digital birth certificate for parts). Selected examples: Chainparency for sustainable farming and aquaculture, Honeywell's Trust Trace™ for aerospace parts, VinAssure™ for wines, Everledger for diamonds, De Beers's Tracr for diamonds, TrustChain™ for jewelry, the IBM Food Trust Consortium for food retail, Provenance Blockchain for financial services, and VeChain for the fashion industry
- **Trackability: Physical logistics tracking and monitoring** (e.g., chain of custody, freight in-transit environment history and compliance, such as temperature and humidity levels). Selected examples: CargoX, dexFreight, Shipchain, Slync, TradeLens, and WaltonChain

It is important to note that in leveraging these blockchain capabilities, it is crucial that off-chain event data are credible and accurate for on-chain records to be deemed trustworthy. Additionally, different tagging levels and data capture technologies come with different costs and capabilities,[71] thus their choices must take into consideration asset characteristics and purposes at hand. For instance, a barcode or QR code with manual scans could be feasible choices for a proof-of-origin of non-complex goods, while RFID tags and sensors (e.g., temperature and humidity meters) would be required when automatic environment monitoring and tracking solutions are sought.

Recordation and Exchange of Commercial Assets

This application category revolves around peer-to-peer exchange of assets on blockchain without trusted intermediaries, for which automatic updates of ledgers and cryptographic tokens are integral parts of the process. Here, cash, digital assets (e.g., software, 3D printing file), or physical assets (e.g., raw materials, goods) can be tokenized, and when exchanged on blockchain, they become *monetizable* assets. For instance, they can be used as intermediary currency in the settlement of other types of assets exchanged on blockchain. This token-based blockchain not only enables direct, simultaneous execution of transaction on both sides, but also allows the transfer of both *ownership* and *value* to be carried out in the same transaction. It does so without trusted third-party intermediaries, thus reducing clearing and settlement times as well as related costs, contrary to traditional methods where there are additional costs and time involved.[72]

Use cases in this application category can be grouped into two brackets for financial and commercial goods/services assets. Example use cases are as follows:[73]

Montecchi, Plangger, Etter 2019; Paliwal, Chandra, and Sharma 2020; PwC 2019; Smith + Crown 2020; Swanson 2017; UCL CBT 2019; Vadgama and Tasca 2021; Yusuf et al. 2018b; Zhang 2019

[71] Bhatia et al. 2019; Paliwal, Chandra, and Sharma 2020

[72] Camerinelli 2018; Deloitte 2018; Iredale 2021; McBeath 2018; Roy 2021; Subbaraman and Krishnan 2021; UCL CBT 2019; Vadgama and Tasca 2021

[73] Bender, Burchardi, and Shepherd 2019; CAICT & Trusted Blockchain Initiatives 2018; Carson et al. 2018; ChainLink Research 2018; Choudary, Van Alstyne, and Parker 2019; Chu and Schatsky 2016; Deloitte 2018; Dutta et al. 2020; PwC 2018; WEF 2018

P2P Financial Transactions

- **Supply chain finance** (e.g., cross-border payment, trade clearing and settlement, insurance claims, supply chain finance, digital bill, account receivable, micropayments such as consumption-based/usage-based payment)
- **Incentives payment with cryptographic tokens.** Examples: Recereum pays crypto coins for exchanging plastic and aluminum bottles and by sorting waste correctly;[74] FishCoin pays a utility token tradable for mobile phone top-up minutes to incentivize fishers to provide for information on their catch;[75] Plastic Bank issues a financial reward in the form of a cryptographic token in exchange for depositing collected ocean recyclable plastics.[76]

P2P Transactions of Goods and Services

- **Peer-to-peer renewable energy trading** (e.g., SunContract, SOLshare and LO3 Energy)
- **Peer-to-peer marketplace.** Example: GrainChain for agricultural commodity trade, with dollar-backed Grainpay stable coin for settlement of the transaction;[77] GoDirect™ Trade marketplace for used serviceable and new surplus parts inventory in aviation;[78] China's Carbon Credit Management Platform for carbon-credit trading.[79]
- **Peer-to-peer spot markets** (e.g., spot market for trucking services; equipment leasing such as vehicle, chassis, and containers; storage space renting).
- **Peer-to-peer tokenized carbon credit trading**
- **Peer-to-peer services.** Example: eMotorWerks's Airbnb for EVs peer-to-peer charging, allowing charging station or home owners to rent out time on their stations to EV drivers participating in the network and receiving payments or carbon credits for the service via digital tokens.[80]

Process Automation

In this application category, smart contracts that use data recorded on blockchain to auto-execute supply chain processes are leveraged. For each invocation of a smart contract, a transaction is created in the network and the ledger is continuously updated by business rules contained in smart contracts in the form of code. The ledger holding the current value of smart-contract data is distributed across the network, allowing all parties to validate the outcome instantaneously and without a need for a third-party intermediary.[81]

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[74] PwC 2018
[75] WEF 2018
[76] Herweijer and Swanborough 2018
[77] Sanka et al. 2021; UCL CBT 2019
[78] Supply Chain Navigator 2020
[79] Herweijer and Swanborough 2018; PwC 2018; WEF 2018
[80] Tabaddor and Sardar 2018
[81] Blechschmidt and Stöcker 2016; Brakeville and Perepa 2017; Chu and Schatsky 2016; Kramer 2020; Küpper 2019

Smart contracts can be used for simple economic transactions like sending money from A to B, or more complex smart contracts that use NFTs for decentralized autonomous organizations (DAOs) can be implemented. In the latter instance, within a smart contract, tokens can be created that represent physical goods and their exchanges may be automatically executed to streamline on-chain and off-chain transactions.[82]

In this application category, legal and process characteristics must be taken into considerations. Although two parties can enter into an *"agreement"* to the use of a smart contract, translating business rules into code does not automatically turn a smart contract into a *"contract"* in a legal sense. In this respect, two practices of smart contracts can be distinguished, namely *code-only smart contracts* and *ancillary smart contracts*.[83] The former is created and deployed as a sole manifestation of the agreement between the parties without any enforceable text-based contract behind them; whereas the latter involves the use of smart contracts as vehicles to execute certain provisions of a text-based contract with specific reference to such use.[84]

In terms of process characteristics, because smart contracts on blockchain function based on "if/then" conditions that are written into codes, adopting smart contracts requires users to determine which tasks are sufficiently *objective* to lend themselves to smart-contract execution. While the objectivity required for smart-contract code does not lend their uses for more *subjective* requirements, smart contracts have a beneficial role in a well-established and easily verifiable transactions.[85] Examples of transactions possessing such characteristics, thus potential use cases are as follows:

- **Automated procurement**
  - **Procure-to-pay processes**[86]
  - **Supplier onboarding.** Self-verification features of smart contracts can be beneficial in supplier onboarding, especially in cases of new suppliers, since all of information is available in the hiring contract.[87]
  - **Contract management.** The entire contract management processes could be completely condensed and redefined with smart contract applications wherein the terms of a contract get enforced automatically[88]
- **Automated supply chain trade documentation.** Blockchain can provide secure, accessible digital versions of letters of credit and bills of lading to all parties in a transaction, and smart contracts can be used to manage the workflow of approvals and automatically transfer payment upon all signatures being collected.[89] Examples: TradeLens' Clearway – trade document module of smart

[82] Blockchain App Factory 2021; Voshmgir 2019b; WEF 2020
[83] Levi and Lipton 2018; Mearian 2019
[84] Levi and Lipton 2018
[85] Block Key Capital 2018; Levi and Lipton 2018; Stawitz 2019
[86] Brody 2019; Pearce, Conde, and Epstein 2019; Narayanan 2020; York 2017
[87] Farr 2018; HDT Trucking Info 2018; Zycus 2018
[88] Brody 2019; MIT CTL 2019; Pearce, Conde, and Epstein 2019; Zycus 2018
[89] Chu and Schatsky 2016

contracts;[90] CargoSmart consortium;[91] CargoX's Blockchain Document Transaction System (BDTS);[92] Letter-of-credit smart contract by Bank of America Merrill Lynch, HSBC, and Infocomm Development Authority of Singapore (IDA)[93]

- **Automated tracking and tracing**
  - **Modifiable goods.** NFTs and the smart contracts enable track-and-trace processes of modifiable goods. This use case would require NFTs which represents all the materials, sub-assemblies and intermediate assemblies of a product, and "token recipes" which resemble the bill of materials as a basis for smart-contract coding to automatically capture token creation, transformation, and exchange. Such capabilities allow various granularity levels of traceability not just the goods itself, but also its inputs.[94]
  - **Automated checkpoint verification.** A blockchain-based traceability system could use smart contracts to ensure that products are verified at key points in the supply chain such as at the production, storage, and retailer stages of the supply chain.
  - **Automated exceptions tracking.** For example, a smart contract might monitor IoT events, such as a temperature alert or GPS-detected shipment delivery.[95]
- **Automated exchange of digital or physical assets.** Trade physical or digital assets; transfer legal ownership of an asset; transfer copyright or IP value; loyalty program.[96]
- **Automated financial transactions.** Example: ShipChain's smart contract automatically execute settlement once the conditions have been met (for example, as soon as the driver transmits confirmation of successful delivery) using ShipChain's digital currency called "SHIP tokens." Participants of ShipChain's platform purchase these tokens in order to pay for freight and settle transactions on the platform.[97]

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[90] Behrens 2019; Lumineau et al. 2021; *Martitime Executive* 2018a; Xia, Grover, and Lieb 2021
[91] *Martitime Executive* 2018b
[92] *Martitime Executive* 2018b; Richter 2019
[93] DHL 2018
[94] Blockchain App Factory 2021; Dasaklis et al. 2019
[95] MIT CTL 2019; Tan, Xuan, and Cottrill 2018
[96] Bender, Burchardi, and Shepherd 2019; Ganeriwalla et al. 2018; Litan 2020
[97] DHL 2018

Lists of Selected Readings

Selected Readings on Blockchain Technology

Articles	Key Areas of Insights
Arun et al (2019) Blockchain Technology Jai Singh Arun, Jerry Cuomo, Nitin Gaur. *Inform IT,* March 25.	Enterprise blockchain technology, tokenization, enterprise integration
CAICT & Trusted Blockchain Initiatives (2018) Blockchain CAICT (China Academy of Information and Communication Technology) and Trusted Blockchain Initiatives. White paper, December.	Blockchain technical architecture, technology development trend, current development across countries, challenges inhibiting mass adoptions
Cummings (2019) The Four Blockchain Generations Stephan Cummings. Medium, February 2.	Evolution of blockchain technology
Ganne (2018) Can Blockchain Revolutionize International Trade? Emmanuelle Ganne. World Trade Organization (WTO) paper	Blockchain technology; applications in international trade
Gupta (2020) Blockchain for Dummies Manav Gupta. 3rd IBM Limited Edition. 2020 by John Wiley & Sons, Inc.	Blockchain technology; applications across industries; Hyperledger; steps for blockchain applications
Hewa et al (2021) Survey on Blockchain Based Smart Contracts: Applications, Opportunities and Challenges Tharaka Hewa, Mika Ylianttila, and Madhusanka Liyanage. *Journal of Network and Computer Applications* 177:102857.	Smart contract ecosystems and comparative advantages of different platforms; applications across industries
Hyperledger (2017) Hyperledger Architecture, Volume 1 Hyperledger. White paper.	Hyperledger layered structure and various types of consensus mechanisms used
Ismail & Materwala (2019) A Review of Blockchain Architecture and Consensus Protocols: Use Cases, Challenges, and Solutions Leila Ismail and Huned Materwala. *Symmetry* 11:1198.	Blockchain architecture, network types, and consensus algorithms
Jalal et al (2020) Study on Public Blockchain Consensus Algorithms: A Systematic Literature Review Islahuddin Jalal, Zarina Shukur, and Khairul Azmi Abu Bakar. Preprints, Posted: 12 November 2020. doi:10.20944/preprints202011.0355.v1	Consensus algorithms and associated issues
Microsoft (2019) Tokenization – An Introduction Microsoft white paper, October 28.	Tokenization, token properties, token use cases
Mobindustry (2020) Designing a Blockchain Architecture: Types, Use Cases, and Challenges	Blockchain data structure and architecture

Articles	Key Areas of Insights
Mobindustry. Medium, November 10.	
Nakamoto (2008) Bitcoin: A Peer-to-Peer Electronic Cash System Satoshi Nakamoto. White paper, October 31.	Blockchain technology behind Bitcoin
Nayyar & Kasthuri (2021) The Blockchain Consortium is Coming of Age Anand Nayyar and Magesh Kasthuri. Open Source For You, February 11.	Comparative discussion of public, private, and consortium blockchains; different types of consortium blockchains; governance model of consortium blockchains
OECD (n.d.) OECD Blockchain Primer Organisation for Economic Co-operation and Development (OECD) publication.	Blockchain architecture, layered structure, key characteristics, and applications across industries
Sabry et al (2019) The Road to the Blockchain Technology: Concept and Types Sana Sabah Sabry, Nada Mahdi Kaittan, Israa Majeed. *Periodicals of Engineering and Natural Sciences* Vol. 7, No. 4, pp.1821-1832.	Blockchain key elements; three types of blockchains – only Cryptocurrency blockchain (C2C), Business to Cryptocurrency blockchain (B2C), and only business blockchain (B2B); comparative review of Bitcoin, Ethereum, and Hyperledger Fabric
Sanka et al (2021) A Survey of Breakthrough in Blockchain Technology: Adoptions, Applications, Challenges and Future Research Abdurrashid Ibrahim Sanka, Muhammad Irfan, Ian Huang, and Ray C.C. Cheung. *Computer Communications* 169:179-201.	Blockchain architecture, consensus mechanisms, cryptography; summary of blockchain applications
Sarmah (2018) Understanding Blockchain Technology Simanta Shekhar Sarmah. *Computer Science and Engineering* 8 (2): 23-29.	Blockchain layered structure, architecture, generations, tokens, advantages and disadvantages
Seibold & Samman (2016) Consensus – Immutable Agreement for the Internet of Value Sigrid Seibold, and George Samman. KPMG paper.	Blockchain ecosystems; evaluation of consensuses used by different blockchains
Srivastava et al (2018) A Systematic Review on Evolution of Blockchain Generations Abhishek Srivastava, Pronaya Bhattacharya, Arunendra Singh, and Atul Mathur. *International Journal of Information Technology and Electrical Engineering* 7 (6): 1-8.	Evolution of blockchain generations
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Zhang (2019) Deploying Blockchain Technology in the Supply Chain Jian Zhang. Open access peer-reviewed chapter. Intech Open, Published: May 28th 2019. DOI: 10.5772/intechopen.86530.	Blockchain technology, data structure, key components, smart contract, and challenges; brief discussion of blockchain benefits for supply chain
Zheng et al (2017) An Overview of Blockchain Technology: Architecture, Consensus, and Future Trends Zibin Zheng, Shaoan Xie, Hong-Ning Dai, Xiangping Chen. 2017 IEEE International Congress on Big Data (BigData Congress), 2017, pp. 557-564	Blockchain architecture and taxonomy; analysis of various consensus algorithms

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Alicke et al. (2017) Blockchain Technology for Supply Chains—A Must or a Maybe? Knut Alicke, Alan Davies, Markus Leopoldseder, and Alex Niemeyer. McKinsey Insights, September 12.	Technical considerations for supply chain applications
Amato-McCoy (2018) Walmart Wants 'Leafy Green' Suppliers on Blockchain Deena M. Amato-McCoy. *Chain Store Age,* September 25.	Walmart Food Traceability Initiative based on IBM blockchain
APQC (2018) How Blockchain Improves Performance in Oil and Gas Supply Chains APQC (American Productivity & Quality Center), June 22.	Blockchain-as-a-service (BaaS) use case scenarios
AWS (2020) Blockchain for Sustainability Amazon Web Services. White paper, December 22	Blockchain with non-fungible token (NFT) for circularity (lifecycle records), auditing/certifications registry, and carbon emission tracking and marketplace
Banerjee (2019) Chapter Nine - Blockchain with IOT: Applications and Use Cases for a New Paradigm of Supply Chain Driving Efficiency and Cost Arnab Banerjee. *Advances in Computers* 115:259–292.	IoT blockchain architecture; Use cases in product/order tracking, traceability, agricultural supply chain, digital automotive, digital homes and offices, distribution industry, and manufacturing systems
Beach (2017) Blockchain Shows Promise for Trucking Jim Beach. *Heavy Duty Trucking (HDT) Trucking Info,* December 15.	Blockchain applications in the trucking industry; Blockchain in Transport Alliance (BiTA)

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Bender et al (2019) Capturing the Value of Blockchain Jan Philipp Bender, Kaj Burchardi, and Neil Shepherd. BCG, April 9.	Blockchain use cases in different industries; blockchain project implementation framework
Bhatia et al (2019) Stamping Out Counterfeit Goods with Blockchain and IoT Akash Bhatia, Zia Yusuf, Usama Gill, Neil Shepherd, Maciej Kranz, and Anoop Nannra. BCG, May 17.	Blockchain with IoT use cases to combat counterfeiting across the product life cycle
Blechschmidt & Stöcker (2016) How Blockchain Can Slash the Manufacturing "Trust Tax" Burkhard Blechschmidt, and Carsten Stöcker. Cognizant white paper.	Everledger blockchain for diamonds; Blockchain smart contract use cases in manufacturing
Brohan (2021) An Aerospace Parts Marketplace Flies High with Blockchain Mark Brohan. *Digital Commerce 360,* January 11.	Blockchain applications in Honeywell's GoDirect Trade for B2B marketplace of aerospace parts
Butters et al (2020) Startups Partner to Link Blockchain and Digital Twins Lisa Butters, Mark Manning, and Daniel Stanton. *Supply & Demand Chain Executive*, April 29.	Blockchain and digital twin applications in Honeywell's GoDirect Trade
Carson et al (2018) Blockchain beyond the Hype: What is the Strategic Business Value? Brant Carson, Giulio Romanelli, Patricia Walsh, and Askhat Zhumaev. McKinsey Insights, June 19.	Blockchain use cases and potential business value across industries
ChainLink Research (2018) Blockchain's Role in the Produce Supply Chain ChainLink Research. Report.	Blockchain applications in produce supply chain
Chu & Schatsky (2016) Upgrading Blockchains: Smart Contract Use Cases in Industry Yang Chu, and David Schatsky. Deloitte University Press, 8 June	Use cases of smart contracts across industries
Close et al (2018) A Prescription for Blockchain in Health Care Karalee Close, Emily Serazin, Alexander Aboshiha, Amy Hurwitz, Lise Lørup, and Nayel Hakim. BCG, April 20.	Potential blockchain applications in healthcare
Cohen (2017) Insights into Blockchain: Opportunities and Challenges across Multiple Industries Lanny Cohen. Capgemini white paper, June.	Blockchain applications across industries with examples from different countries
Cottrill (2018) The Benefits of Blockchain: Fact or Wishful Thinking? Cottrill, Ken. *Supply Chain Management Review*. Jan/Feb, Vol. 22 Issue 1, p20-25.	Blockchain applications in supply chain

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Dasaklis et al (2019) A Framework for Supply Chain Traceability Based on Blockchain Tokens Thomas K. Dasaklis, Fran Casino, Costas Patsakis, and Christos Douligeri. BPM 2019 Workshops, LNBIP 362, pp. 704–716.	Token-based blockchain framework for supply chain traceability based on BOM approach
Dash, Majumdar & Gunjikar (2017) Blockchain: A Healthcare Industry View Sharmistha Dash, Anirban Majumdar, and Prasanna Gunjikar. Capgemini white paper, April.	Blockchain use cases in healthcare
de Chillaz et al (2021) The Value of a Blockchain-Enabled Supply Chain Damien de Chillaz, Adrien Calvayrac, Jörg Junghanns, and Jean-Baptiste Meriem. Capgemini series.	Blockchain use cases in supply chain management
Deloitte (2018) Blockchain: A Technical Primer Deloitte Insights, February 6.	Blockchain utilization levels and applications across industries
DHL (2018) Blockchain in Logistics DHL Trend Research.	Blockchain applications in logistics
Dutta et al (2020) Blockchain Technology in Supply Chain Operations: Applications, Challenges and Research Opportunities Pankaj Dutta, Tsan-Ming Choi, Surabhi Somani, and Richa Butala. *Transportation Research Part E: Logistics and Transportation Review* 142:102067.	Blockchain applications in supply chain management across operations areas and industries
Fedder, Renner & Upadhyaya (2018) The Adoption of Disruptive Technologies in the Consumer Products Industry: Spotlight on Blockchain Curt Fedder, Barb Renner, and Jagadish Upadhyaya. Deloitte Insights, December 11.	Potential blockchain value and use cases in consumer products industry
Fretty (2020) Do Your Production Processes Brew Transparency? Peter Fretty. *Industry Week,* July 15	J. M. Smucker Co. blockchain applications for coffee country-of-origin provenance and farmer connections
Gandhi, Majumdar & Monahan (2018) Unlocking Blockchain's Potential in Your Supply Chain Gandhi, Suketu; Majumdar, Adrish; Monahan, Sean. *Supply Chain Management Review,* Jul/Aug Volume 22 Issue 4, p38-40.	Blockchain use cases in supply chain with examples of companies using the technology
Ganne (2018) Can Blockchain Revolutionize International Trade? Emmanuelle Ganne. World Trade Organization (WTO) paper	Blockchain technology; applications in international trade

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Gaur & Gaiha (2020) Building a Transparent Supply Chain Gaur, Vishal; Gaiha, Abhinav. *Harvard Business Review,* May/Jun, Vol. 98 Issue 3, p94-103.	Blockchain applications in supply chain
Gupta (2020) Blockchain for Dummies Manav Gupta. 3rd IBM Limited Edition. 2020 by John Wiley & Sons, Inc.	Blockchain technology; applications across industries; Hyperledger; steps for blockchain applications
Hammoud et al (2019) An Investor's Guide to Blockchain in Fraud and Loss Prevention Tawfik Hammoud, Jonathan Croog, Prabhpal Grewal, and James Plumb. BCG, June 26.	Value of blockchain in fraud and loss prevention across industries
Hanebeck (2020) Rebuilding Trust on Federal Highways: How Blockchain Enables New Business Models Hanns-Christian Hanebeck. World Economic Forum, April 30.	Blockchain applications in highway administrations *Note: certain applications discussed are applicable in business logistics settings*
Haughwout (2017) Blockchain: A Single, Immutable, Serialized Source of Truth Jim Haughwout. *MH&L,* October 18.	Blockchain advantages; Applications in supply chain and logistics management
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Herweijer & Swanborough (2018) 8 Ways Blockchain Can Be an Environmental Game-Changer Celine Herweijer, and Jahda Swanborough. World Economic Forum, September 19.	Blockchain use cases to enable sustainability initiatives
Hewa et al (2021) Survey on Blockchain Based Smart Contracts: Applications, Opportunities and Challenges Tharaka Hewa, Mika Ylianttila, and Madhusanka Liyanage. *Journal of Network and Computer Applications* 177:102857.	Smart contract ecosystems and comparative advantages of different platforms; applications across industries
Industry Week **(2018) Major Automakers, Startups Launch Mobility Open Blockchain Initiative** IW Staff. *Industry Week,* May 2.	Mobility Open Blockchain Initiative (MOBI) consortium and applications in the automotive industry
Jenks (2021) Blockchain Technology Reshaping SCM! Sam Jenks. *Supply Chain Game Changer,* April 27.	Blockchain applications in logistics and procurement
Küpper (2019) Blockchain in the Factory of the Future Daniel Küpper, Johannes Ströhle, Thomas Krüger, Kaj Burchardi, and Neil Shepherd. BCG, July 15.	Blockchain applications in operations management
LaneAxis (2018) Blockchain-Based Shipper/Carrier Direct Optimization Platform LaneAxis. White paper, August 9	Features, thus use cases, of LaneAxis blockchain for freight logistics management

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Litan (2020) Smart Contracts Are Neither Smart Nor Are They Contracts Avivah Litan. Gartner blog, March 3.	Consideration factors in implementing smart contracts
Loop (2017) Blockchain: The Next Evolution of Supply Chains Peter Loop. *Industry Week,* January 13	Use cases in supply chain and retails
Marsh (2018) Blockchain Could Help DTNA Accelerate Parts, Maintenance Aaron Marsh. *Fleet Owner,* November 15	Daimler Trucks North America (DTNA) blockchain project for aftermarket remanufacturing operations
***Maritime Executive* (2018) Maersk's Blockchain Solution: Ready, Set, Go!** The Maritime Executive, August 9.	Features of TradeLens, a blockchain consortium and solutions for global trade introduced by Maersk and IBM
***Maritime Executive* (2018) Certificate of Origin Blockchain Platform Launched** *The Martitime Executive,* May 8.	World first blockchain-based electronic certificates of origin (eCO) platform by Singapore International Chamber of Commerce (SICC)
McCauley (2020) Why Big Pharma Is Betting on Blockchain McCauley, Alison. Harvard Business Review, May 29, 2-5.	MediLedger Network, a blockchain consortium focused on pharma supply chains
Microsoft (2018) How Blockchain Will Transform the Modern Supply Chain Microsoft white paper	Blockchain use cases in supply chain management
Microsoft (2019) Tokenization – An Introduction Microsoft white paper, October 28.	Tokenization, token properties, token use cases
MIT CTL (2019) A Consensus on the Truth? Blockchain Applications in Supply Chain Management The MIT Center for Transportation & Logistics (MIT CTL), April 25. Summary Reports of Roundtable events October, 2017 and 2018.	Blockchain applications in supply chain, challenges, and outlooks
Monarch (2018) Blockchain Can Improve Driver Pay and Recruit the Best Truckers John Monarch. Truck.com, November 15.	Blockchain use cases for driver compensation and recruitment
Montecchi et al (2019) It's Real, Trust Me! Establishing Supply Chain Provenance Using Blockchain Matteo Montecchi, Kirk Plangger, Michael Etter. *Business Horizons* 62 (3), May 15.	Blockchain capabilities and enablement of provenance knowledge in supply chains
Narayanan (2020) Leveraging Blockchain to Reimagine Dispute Management Sreerag Narayanan. Capgemini white paper.	Smart contract applications in order-to-delivery (OTD) process
NPD (2018) An Introduction to Blockchain, and What it Means for Retail's Future	Blockchain potential applications in retails and limitations to consider

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Peshkam & Dubois (2019) How Blockchain Can Win the War Against Plastic Waste Michael Peshkam, and David Dubois. INSEAD, blog July 24.	Various blockchain projects aimed to address plastic waste
Pradhan et al (2018) Blockchain Fundamentals for Supply Chain: A Guide to the New Boardroom Buzzword Alex Pradhan, Andrew Stevens, and John Johnson. Gartner, February 23.	Key elements of blockchain; application trends in supply chain; current challenges
PwC (2018) Building Block(Chain)s for a Better Planet PwC, Fourth Industrial Revolution for the Earth Series, September.	Blockchain capabilities; use cases that address various environmental issues
PwC (2019) How Can Blockchain Power Industrial Manufacturing? PwC publication.	Blockchain applications in the aerospace and automotive industries.
Retail Week Connect (2018) Blockchain: The Future of the Supply Chain Retail Week Connect, white paper, in association with IBM.	Blockchain applications in retails, with example projects
Roy (2021) Can Blockchain Unblock Supply Chain? Sanjeev Kumar Roy. *Supply Chain Game Changer,* June 1.	Blockchain values; applications in supply chains; implementation challenges
Schmahl et al (2019) Resolving the Blockchain Paradox in Transportation and Logistics Andrew Schmahl, Kaj Burchardi, Camille Egloff, Jacqueline Govers, Ted Chan, and Markos Giakoumelos. BCG, January 29.	Blockchain applications in transport and logistics
SCQ (2020) eProvenance Uncorks VinAssure™, an IBM Blockchain-Powered Platform for the Wine Industry *Supply Chain Quarterly,* December 15.	Features of eProvenance's VinAssure™ built on IBM Blockchain for the wine industry
***Supply Chain Navigator* (2020) Honeywell's GoDirect™ Trade Leverages Blockchain to Overhaul Aircraft Parts Aftermarket** *Supply Chain Navigator,* Spring.	Features of Honeywell's GoDirect™ project development and features
***Sustainable Brands* (2018) IBM TrustChain Tracks Diamonds from Mine to Finger** *Sustainable Brands,* May 1.	Features of TrustChain™ Initiative for provenance of finished pieces of jewelry
Tan, Xuan & Cottrill (2018) Is Blockchain the Missing Link in the Halal Supply Chain?	A blockchain-based traceability system for Halal-certified supply chains

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UCL CBT (2019) Distributed Ledger Technology in the Supply Chain University College London Centre for Blockchain Technologies (UCL CBT). Report.	Analysis of over 100 blockchain projects in the retail physical supply chain domain, including use case–specific analysis in product tracing, logistics, financial transactions, retail operations, and circular economy
Vadgama & Tasca (2021) An Analysis of Blockchain Adoption in Supply Chains Between 2010 and 2020 Nikhil Vadgama and Paolo Tasca. *Frontiers in Blockchain,* March 23.	Analysis of 271 blockchain projects on parameters such as their inception dates, types of blockchain, status, sectors applied to and type of organization that founded the project
Van Hoek et al (2020) Pain of the Chain Remko Van Hoek, Brian Fugate, Marat Davletshin, and Matthew A. Waller. *Supply Chain Quarterly,* May 19.	Matrix for value of blockchain for supply networks, with example blockchains in different value quadrants
Weingärtner (n.d.) Tokenization of Physical Assets and the Impact of IoT and AI Tim Weingärtner. Research paper, released by European Union Blockchain Observatory and Forum.	Tokenized assets; blockchain-IoT five domains of use cases; blockchain-AI applications
Xia, Grover & Lieb (2021) Keeping PACE with Blockchain in Ocean Transportation Yu Amy Xia; Grover, Shilpi; Lieb, Robert C. *Supply Chain Management Review,* Mar/Apr, Vol. 25 Issue 3/4, p32-39.	Introduce PACE—Permissioned, Authorization, Consolidation and Expansion—vision for supply chain management using blockchain, with blockchain project examples
Yusuf et al (2018) Pairing Blockchain with IoT to Cut Supply Chain Costs Zia Yusuf, Akash Bhatia, Usama Gill, Maciej Kranz, Michelle Fleury, and Anoop Nannra. BCG, December 18.	Blockchain-IoT use cases in supply chain management
Yusuf et al (2018) Are Blockchain and the Internet of Things Made for Each Other? Zia Yusuf, Akash Bhatia, Massimo Russo, Usama Gill, Maciej Kranz, and Anoop Nannra. BCG, July 30.	Blockchain-IoT use cases in businesses, and their short-term and mid/long-term values

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