A Blockchain Tutorial

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Blockchain is a recently-developed distributed digital implementation of the hardcopy transaction *ledger* that has been used throughout the world for centuries. Businesses and other organizations use ledgers in a variety of applications, such as to determine ownership, establish valuations, and document liabilities. The most common ledger applications are for tracking and chronologically recording transactions that involve an exchange of value between parties. Another common use of ledgers is to record birth and death certificates.

Blockchain first came to public notice as the technology that supports the virtual currency *Bitcoin.* And while the interest in Bitcoin has tended to wax and wane, the interest in blockchain continues to grow[1].

Distributed Ledgers

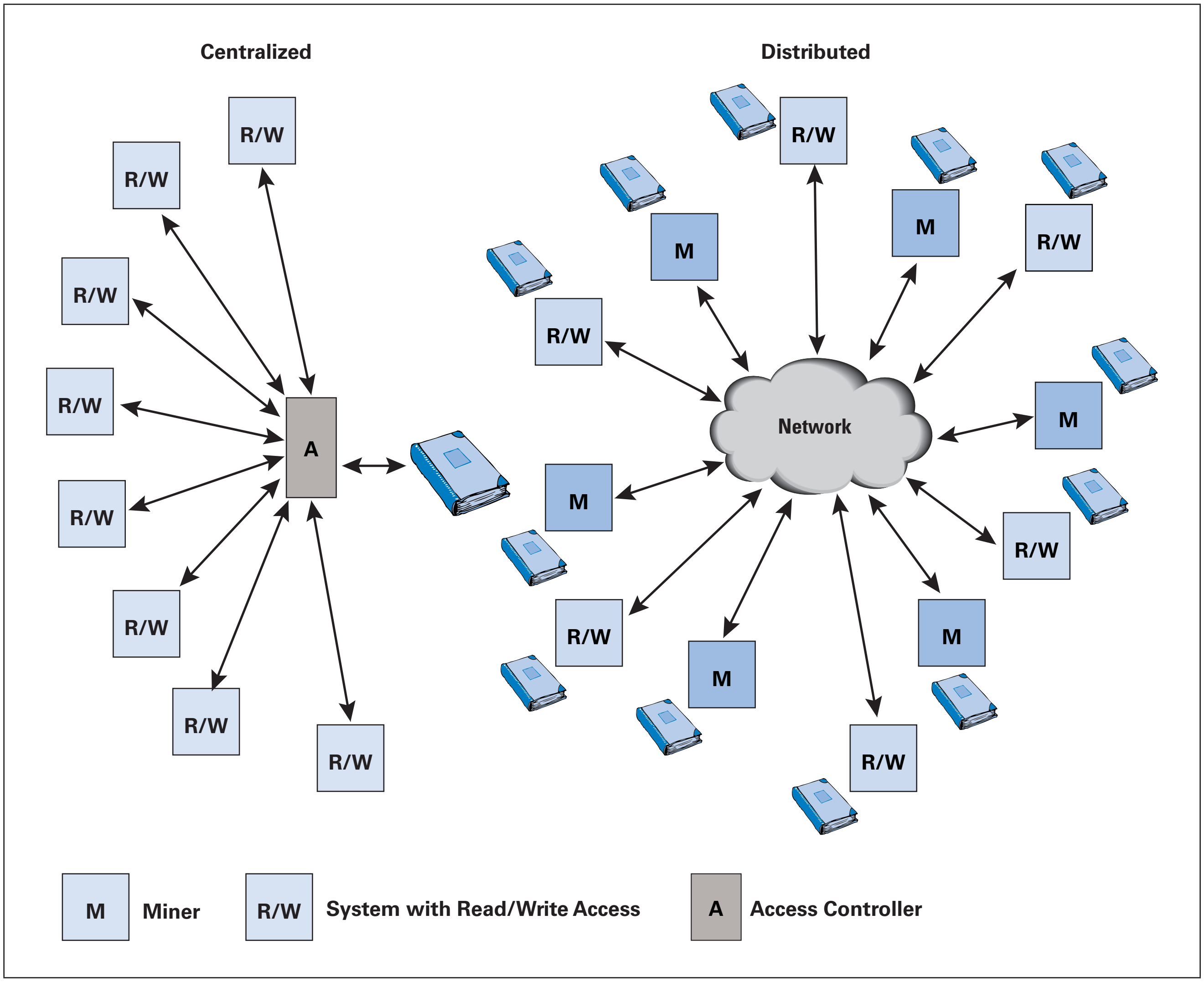
In the business context, a ledger, or *general ledger,* is defined as a central repository of the accounting information of an organization in which the summaries of all financial transactions during an accounting period are recorded. Also called the *book of final entry,* it provides all the data for preparing financial statements for the organization. As mentioned, the ledger can be used to record other types of transactions as well.

In the common business environment, a digital ledger is stored in a central server, and distributed access is provided with read and/or read/write privileges (Figure 1). To assure security, there is some sort of access control mechanism that authenticates users, enables secure access, and enforces access restrictions (for example, read-only). For a system with ongoing transactions and a heavy volume of read and write access, the central server model can be inefficient.

An alternative is a *secure distributed ledger,* which consists of an expandable list of cryptographically signed, irrevocable records of transactions that is shared by a distributed network of computers. Subject to network time delays, every participant has the same copy of the ledger. Each participant may propose a new transaction to be added to the ledger and when consensus that the transaction is valid is reached, it is added to the register.

Trust in a distributed ledger involves two concepts. First, security protocols and mechanisms, generally based on *Public-Key Cryptography,* ensure that the creator of each transaction is authenticated and validated. Transaction creators prove they are entitled to make a transaction by satisfying the particular conditions associated with this application. Meeting these conditions almost always involves the use of a secure digital signature.

Figure 1: Centralized and Distributed Ledgers



Second, a consensus mechanism is used in which computers on the network check each other to ensure records are consistent. In blockchain, this latter mechanism is implemented by systems called *miners*. Their job it is to determine that each new addition to the ledger is valid and consistent with previous entries. When the miners achieve consensus on a new entry, it is permanently added to the ledger.

Consider the use of a distributed ledger to record financial transactions or some other type of transaction that involves the exchange of value. Each transaction is a signed message that creates new outputs (transfer of value to another) while consuming old inputs (transfer of value from the transaction maker). For financial applications, each transaction is the digital equivalent of a paper check, and represents a promise by the payer to transfer control of a given amount of value to another party. The same funds or other value can be sent to only one party. An attempt at double spending, by creating two transactions that consume the same inputs, is prevented by the use of digital signatures and the trust mechanisms of the distributed ledger.

The Gartner Research document "What CIOs Should Tell the Board of Directors About Blockchain"[2] lists the following benefits of using secure distributed ledgers:

- Civilians and computerized agents govern the economic and transaction infrastructure, which is global in scale, peer-to-peer, self-regulating, secure, and reliable.
- A decentralized, shared history of activity, obligations, rights, and records ensures transparency and certainty.
- Fine-grained and diverse (not just monetary) value exchange occurs directly between participants on a network, at lower cost and higher speed compared to legacy systems.
- The system is open to everyone, both public and private, but control and openness can be customized.
- Ownership and rights are recognized broadly. Value can be natively created and exchanged with no double spending or repudiation of transactions. The system guarantees proof of existence, process, and asset provenance.
- Embedded business logic enables dynamically self-executing smart contracts linked to diverse assets.
- Distributed autonomous organizations acting as full-fledged legal entities can execute transactions with no human intervention.

General Concept

In essence, blockchain is a data structure that makes it possible to create a digital ledger of transactions and share it among a distributed network of computers. After a block of data is recorded on the blockchain ledger, it is computationally infeasible to change or remove it. When someone wants to add to the ledger, participants in the network, all of which have copies of the existing blockchain, run algorithms to validate the proposed transaction. If a majority of nodes agree that the transaction looks valid—that is, identifying information matches the history of a blockchain—then the new transaction will be approved and a new block added to the chain. The transaction is fulfilled or executed only when it has been approved for addition to the blockchain. In contrast, in a typical computerized ledger scheme, transactions are submitted to a trusted central party that is responsible for validating the transactions and posting them in the ledger.

Blockchain provides a distributed public ledger containing transactions that are governed and maintained by specific protocols through consensus of the nodes participating in its network. The ledger consists of a linear time-sequenced chain of blocks, with each block containing one or more transactions. Each block is connected to the previous block via a hash (tamper-proof digital fingerprint). On the blockchain, users can observe transactions that have occurred, so they know which outputs are available for spending and which ones have been consumed.

Each block in the blockchain represents, in effect, the claim by someone on the network that the transactions contained inside the block are the first ones to spend the inputs involved, and therefore any transaction in the future that attempts to spend the same inputs should be rejected as invalid.

The term "blockchain" is used interchangeably to describe both the blockchain network (network of nodes) and the distributed ledger (chain of blocks). It offers a way for users who may not know or trust each other to create a record of *who* transacts *what* that will compel the assent of everyone concerned.

The blockchain ledger is not housed on a single privileged server. Rather, it is a shared data structure in which every node (user) on the network has the same copy of all other nodes (subject to propagation time delays) and can read any transaction in the ledger.

Blockchain Structure

A blockchain is a linear sequence of blocks used to store transactions. Each block contains one or more related transactions, and the blocks are ordered in increasing time sequence. Thus, each block represents a set of events that have occurred over a given time frame that is subsequent to the preceding block in the chain and prior to the following block in the chain. Users with application access to the chain can read any transaction in the sequence and can add a new block at the end of the sequence.

As shown in Figure 2, each block has a unique predecessor and successor. A block is added only at the newer, or higher end of the chain. As will be shown, there may temporarily be a branching structure as the chain grows. An essential element of blockchain is that each block is linked to its preceding block using a cryptographic algorithm. The scheme is designed such that it is computationally feasible to add a new block to the end of the chain but computationally infeasible to replace a block interior to the chain or to insert a new block between two existing blocks in the chain. After a block is added to the chain, it is read-only. Figure 3 shows the blockchain operation in general terms.

Figure 2: Block Chaining Concepts

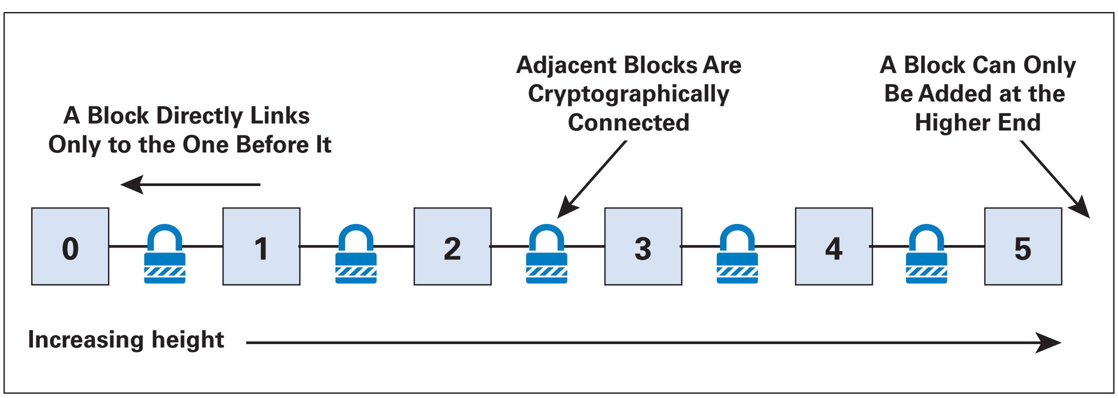
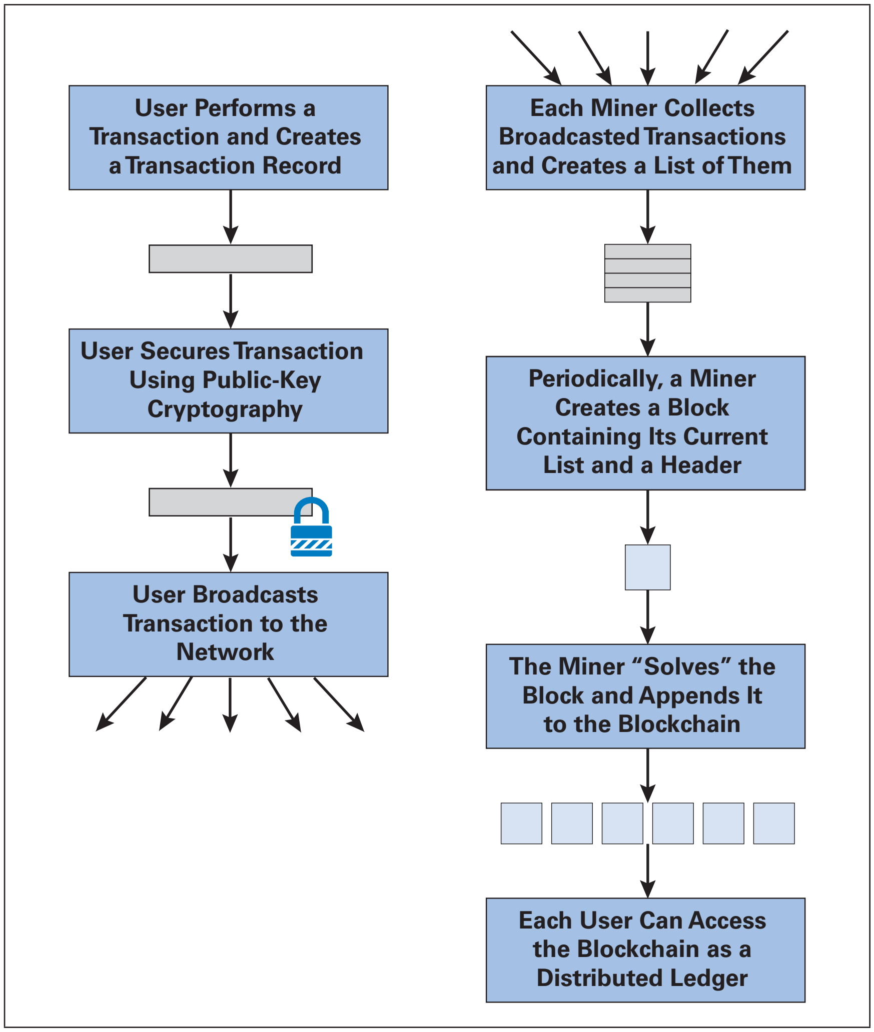


Figure 3: Basic Blockchain Logic



The exact structure of a block may vary from one application to another. Table 1 shows the typical block format. Each block begins with a "magic number" that uniquely identifies this chain. For Bitcoin, the magic number is 0xD9B4BEF9. This number is followed by a *blocksize* field that specifies the total number of bytes in the remainder of the block. Next comes the header, consisting of multiple fields. Finally, the block contains a transaction counter (≥1) followed by one or more transactions. The internal format of each transaction is application-dependent.

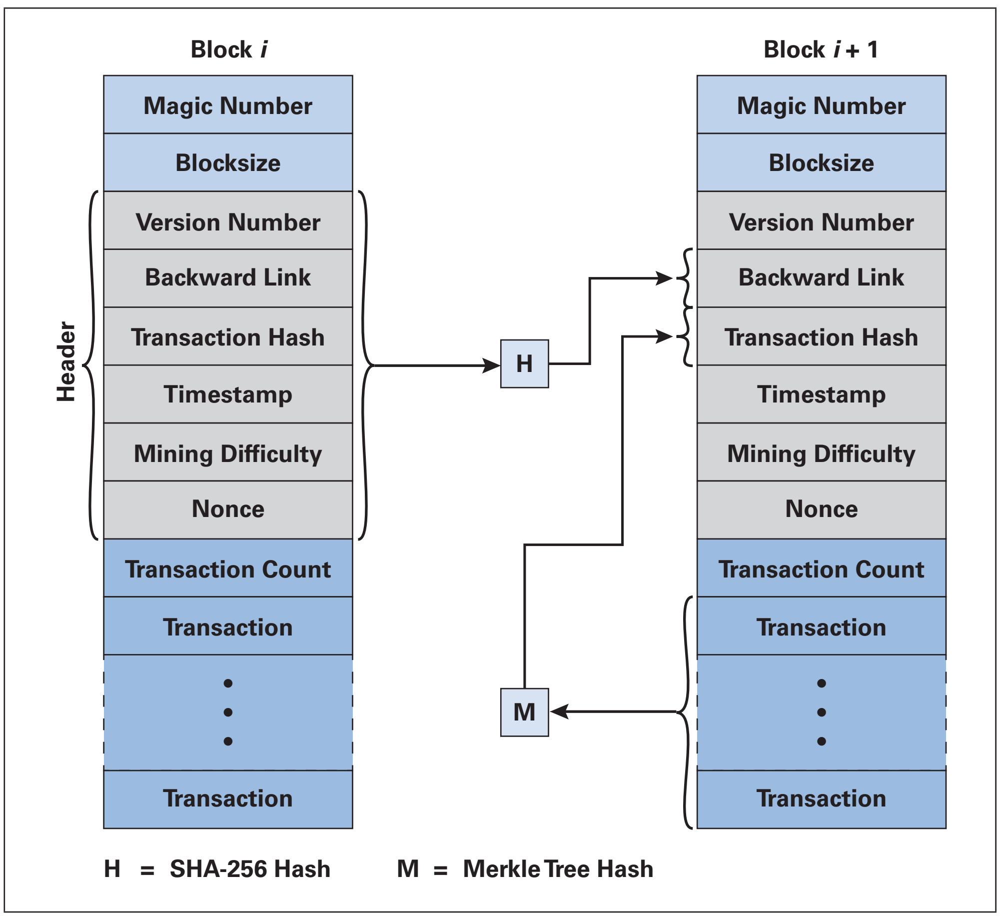
The header begins with a *Version Number,* to allow for future alterations to the block format. The blockchain application should be backward compatible so that older format versions can be processed. The foundation of the security of blockchain is found in the second field, which in effect provides a *Backward Link* to the preceding block. This backward link consists of the hash of all of the headers of the preceding block (Figure 4). By using a cryptographically strong hash function, such as SHA-256, this scheme secures the blockchain against an adversary's altering a block or inserting a block.

In either case, the adversary would have to create a block with a header whose hash value equals a given value, and this creation is computationally infeasible for SHA-256.

Table 1: Contents of a Block

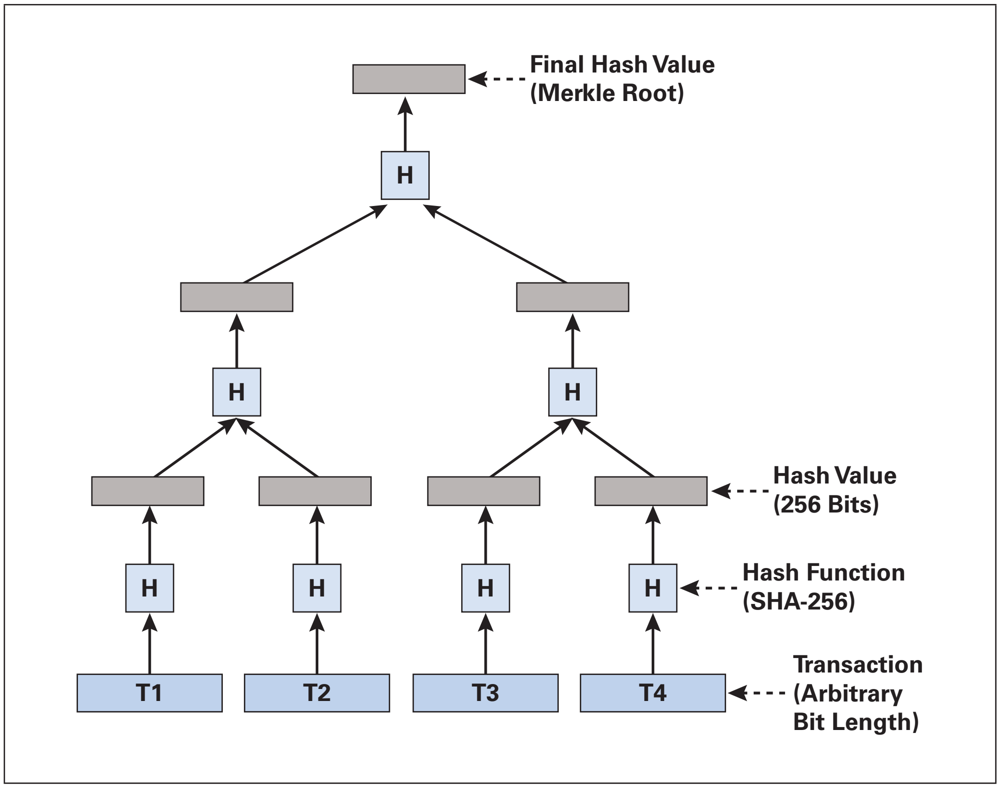
Item	Description
Magic Number	A unique identifier for the blockchain; remains constant for all subsequent blocks
Blocksize	Number of bytes following up to end of block
Version Number	Block format version
Link to Previous Block	Hash of preceding block header
Transaction Hash	The root node of a Merkle Tree, a descendant of all the hashed pairs in the tree. The root node is a 256-bit hash based on all of the transactions in the block.
Timestamp	When block was created
Mining Difficulty	A relative measure of how difficult it is to find a new block. The difficulty is adjusted periodically as a function of how much hashing power has been deployed by the network of miners.
Nonce	Used to calculate proof-of-work
Transaction Counter	Number of transactions in this block
Transactions	The (nonempty) list of transactions

Figure 4: Linkage Between Blocks



The next header field is the *Transaction Hash*. This hash value is computed from the set of data blocks that comprise the list of transactions. Rather than a single hash over this entire set, a *Merkle Tree* technique is used, illustrated in Figure 5. The transaction blocks are processed in pairs; if there is an odd number of transactions, the last transaction on the list is duplicated. Then, each pair of blocks is concatenated to form a binary block that is input to a hash function, typically SHA-256, which produces a 256-bit hash value. The resulting hash values are again paired, and each 512-bit pair is used as input to the hash function. This process continues until a single hash value results, known as the *Merkle Root*.

Figure 5: Example of a Merkle Tree



Following the transaction hash in the header is the *Timestamp* field, which indicates the relative time that this block was created, using a scheme specific to the application.

The next field, *Mining Difficulty,* is a measure of how difficult it is to find a new block. This procedure is explained subsequently. Finally, a one-time *Nonce* value is generated that is used for the proof-of-work concept, described subsequently.

Blockchain Mining

Consider an application that requires the storage of time-sequenced transactions for a distributed group of users. Numerous security issues arise, including authenticating users and ensuring the integrity of the sequence of stored transactions.

The latter includes the need for mechanisms to protect against malicious altering or insertion of transactions. Traditionally, these requirements are met by one or more trusted third parties that act as middleman. In a distributed environment with a large population of users, a peer-to-peer approach becomes more attractive as an efficient method for meeting these requirements. Such an approach is used in blockchain.

The distributed blockchain environment has the following characteristics:[3]

- Each user has a copy of the blockchain.
- Each user running the blockchain client is part of the network.
- New blocks are broadcast to the network.
- Each user updates its local copy of the blockchain.
- If a user is behind the current height of the chain, it can ask other nodes for copies of the blocks needed to catch up.
- If every user has a copy of the blockchain, when the blockchain is queried, every user gets the same answer.

Within a given application, blocks are created periodically to be added to the chain. The linking of a new block to the end of the chain is most commonly done by a process called *mining*.

Each block in the blockchain is required to have evidence that a costly, nonreversible sacrifice of time and energy has been dedicated to that particular block and no others. This evidence is known as *Proof-of-Work*. The important characteristics of proof-of-work include that it represents a true sacrifice: the actions performed are absolutely useless for any purpose other than producing the proof; and that it is nonreversible: no matter what happens, the resources used to produce the proof cannot be recovered. When Bitcoin clients encounter two valid but different blockchains, they choose to accept the one that represents the highest total proof-of-work.

Some entities within a blockchain network act as miners. It is the task of the miners to add new blocks to the chain and, in effect, miners compete to do this task. Any user can create a set of transactions that are to be formed into a block and added to the end of the chain. The miners are a distributed, pooled resource that create the blocks and add them to the chain.

In a typical open, distributed blockchain application, there are no designated miners. The entity adding the next block to the chain is selected on a per-block basis based on whoever in the world chooses to produce the most proof-of-work. In effect, miners compete for the right to add the next block. The incentive for doing so is a reward based on the application, such as earning Bitcoins for adding to the Bitcoin blockchain.

Miners can enter the system without asking for or requiring anyone's permission, and the network will continue to operate seamlessly when any particular miner leaves the system. The system is kept stable by virtue of the nonrecoverable sacrifice and its ability to discourage non-cooperating miners.

The operation of the miners is governed by a *consensus protocol*. In general, a consensus protocol takes as an input the requests of the components and decides upon one of these requests[4]. The blockchain consensus protocol ensures that among multiple conflicting proposed transactions, only one gets approved, preventing for example a double spending of the same coins.

A miner constructs a new block in the following fashion: Users broadcast transactions onto the network to be added to a new block. A miner collects these transactions to form a pool of transactions that are not yet part of a block.

Periodically, the miner constructs a new block with the pool of transactions it currently has. The miner validates all the transactions and decides on an ordering within the block. The miner then invests considerable computational effort to construct a new block; this process is called *solving* a block. This block is then broadcast to all the miners on the network and tentatively added to the end of the blockchain. The application requires that each block prove a significant amount of work was invested in its creation to ensure that untrustworthy peers who want to modify past blocks have to work harder than honest peers who only want to add new blocks to the blockchain.

In effect, the consensus mechanism for blockchain is a lottery race, in which the winner is rewarded in some fashion. The winner is the miner that is able to add a new block to the chain that is accepted by other miners.

The technique that is used for the proof-of-work may differ for different applications. Bitcoin uses a *cryptographic hash* technique that works as follows[5]: The cryptographic hash value of the block header is calculated to form the backward link used by the next block in the chain. If any hash value is allowed, this operation is a simple one. To make the process more resource intensive, a *mining difficulty* is established, which defines how many leading zeros the header hash value must have. Thus, with a mining difficulty of 1, there must be one leading zero. The miner can vary the hash value of the header by varying the value of the nonce field. Typically, a miner will begin with the nonce equal to 1, calculate the hash, and see if it satisfies the difficulty requirement. If not, it increments the nonce and tries again, repeating the process until a hash value is produced that satisfies the difficulty measure.

This difficulty measure is simple to express and effective. For example, if a single leading zero is required, then half of the possible hash values meet the requirement; thus, on average every other hash attempt will result in a hit. If ten leading zeros are required, the level of effort is on the order of one thousand hash attempts. If twenty leading zeros are required, the level of effort is on the order of one million hash attempts. For the Bitcoin blockchain, the target time for solving a block is 10 minutes.

We can express the mining function as follows: For a difficulty level of *alpha,* the hash value *H* must satisfy the following inequality:

H(version number, backward link, transaction hash, timestamp, alpha, nonce) < alpha

The miner must choose a value of nonce that satisfies this inequality. For a secure hash function such as SHA-256, it is effectively impossible to guess a value of nonce that works. Instead, the miner must try out many different values of nonce (using much computing power) until the condition is satisfied. Moreover, the lower the value of alpha, the harder it is to satisfy the condition. A proposed solution, however, can easily be verified. That is, once the nonce value is fixed, it is easy to determine if *H(version number, backward link, transaction hash, timestamp, alpha, nonce)* is less than *alpha*.

A new block can be added to the Bitcoin blockchain only if its header hash is at least as challenging as a difficulty value expected by the consensus protocol. Every 2,016 blocks, the network uses timestamps stored in each block header to calculate the number of seconds elapsed between generation of the first and last of those last 2,016 blocks. The ideal value is 1,209,600 seconds (2 weeks). That is, if blocks are generated at a rate of once per 10 minutes (600 seconds), then 2,016 blocks should be generated in 2,016 × 600 = 1,209,600 seconds. If it took fewer than 2 weeks to generate the 2,016 blocks, the expected difficulty value is increased proportionally (by as much as 300%) so that the next 2,016 blocks should take exactly 2 weeks to generate if hashes are checked at the same rate. If it took more than 2 weeks to generate the blocks, the expected difficulty value is decreased proportionally (by as much as 75%) for the same reason.

Returning to a general discussion of blockchain, not specific to Bitcoin, we can now see how the interlocking values of the nonce, transaction hash, and header hash protect the blockchain. An adversary who wishes to successfully alter the transaction list is faced with two alternative challenges: (1) modify the transaction list in such a way that the transaction hash is unchanged, also leaving the header hash unchanged; this modification is computationally infeasible for a secure hash function such as SHA-256; or (2) allow the transaction hash to change but modify the nonce so that the header hash is unchanged; again, this modification is computationally infeasible. Similarly, to insert a new block interior to the chain, the adversary would have to find a nonce value so that the header hash of the inserted block equals that of the preceding block.

Note that the computational effort of the adversary is far greater than that of the miner. Using the Bitcoin difficulty measure, for example, a difficulty value of 30 means that 2^{226} possible hash values can satisfy the requirement and the level of effort is on the order of 2^{30} hash attempts. For an adversary, it is necessary to find a nonce value that will produce a given unique hash value out of the 2^{256} possible values. On average, this discovery will take about 2^{128} hash attempts.

Miner Selection

The *Proof-of-Work* mechanism discussed previously is a way of selecting which miner gets to append a block to the chain. As we have seen, in this scheme the miner is essentially chosen at random through the competition among miners to produce a proof-of-work that is costly to produce but easy to verify.

Other than proof-of-work, numerous alternative methods have been considered or implemented, including the following[6]:

Proof-of-Stake grants mining rights to participants in proportion to their holding of the currency within the blockchain network. Miners must demonstrate that they hold more than a threshold amount of currency to be able to mine blocks. Proof-of-stake blockchains provide protection from a malicious attack because executing an attack would require the attackers to own a large amount of currency, which is very expensive. Besides, the miners owning a large stake most probably won't attack the system, for example, through double spending. Over time, such attacks will decrease the value of the cryptocurrency and the value of their stake.

The *Proof-of-Burn* process involves destroying Bitcoins by consuming them in a way that does not generate new Bitcoins[7]. The idea is that miners should show proof that they burned some coins—that is, sent them to a verifiably unspendable address. This process is expensive from their individual point of view, just like proof-of-work; but it consumes no resources other than the burned underlying asset. To date, all proof-of-burn cryptocurrencies work by burning proof-of-work-mined cryptocurrencies, so the ultimate source of scarcity remains the proof-of-work-mined "fuel."

Permacoin has proposed a modification to Bitcoin[8], which uses *Proof-of-Retrievability* (POR) to re-purpose the mining resource of Bitcoin to distributed storage of archival data. A POR proves that a node is investing memory or storage resources to store a target file or file fragment. This approach provides additional incentives to contribute resources to the network.

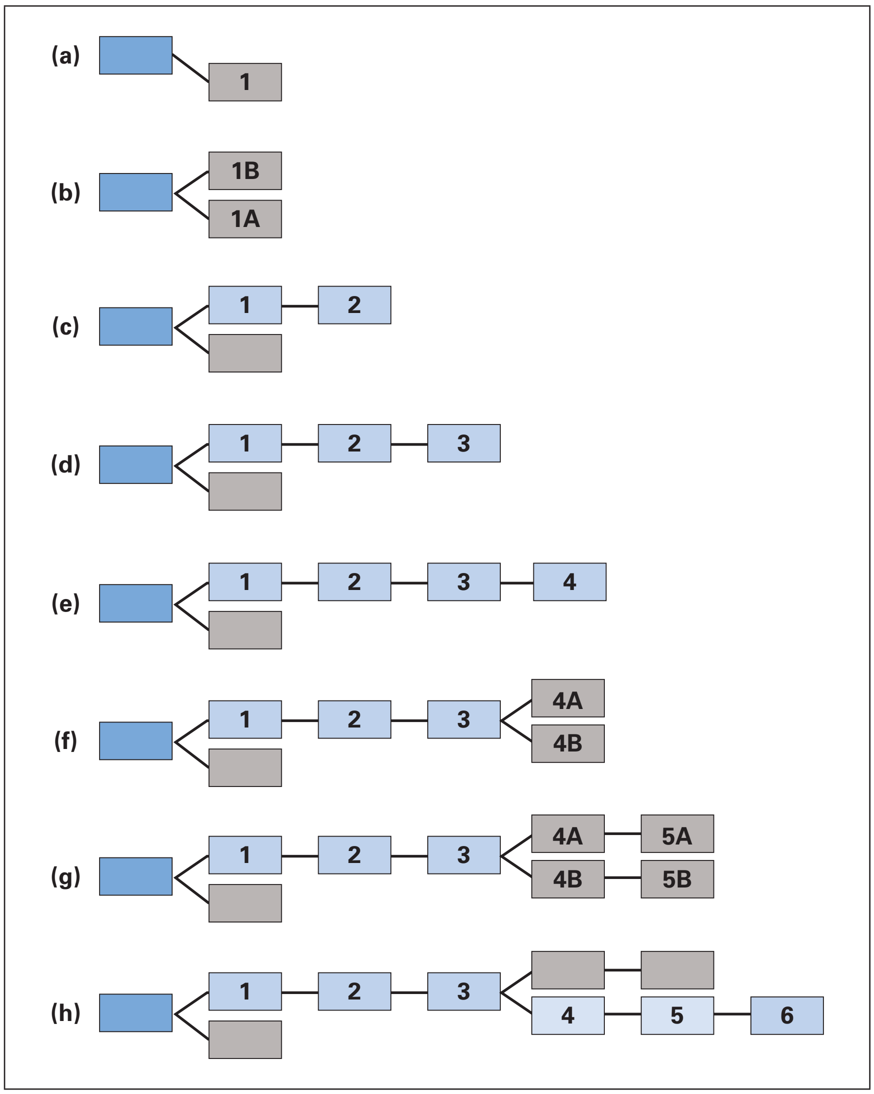
Building the Chain

After a miner has successfully hashed a block header, by finding a nonce value that satisfies the difficulty requirement, the miner can add the block to the end of the chain. It can happen that multiple blocks are created with the same height (distance from the origin block).

This situation occurs if more than one miner, working on different transactions, each produces a block at roughly the same time. This situation creates an apparent fork in the blockchain. Because the blockchain must be a linear, time-ordered sequence, the blocks in the branches following the fork are only provisional. The conflict is resolved when one of the branches exceeds the length of any competing branches.

Figure 6, based on [9], illustrates a typical sequence of events that resolves conflicts. There is an initial block at height 0. All miners try to solve the next block, and one miner solves a block at height 1 (see row *a* in the figure). But at almost the same time, another miner solves a block (row *b*). Block 1A may contain different transactions from 1B, and the users and miners in the network don't know which block should be the accepted one. So, both blocks are considered as provisional, and some miners work on adding to the chain at 1A, and some at 1B.

Figure 6: Adding Blocks to a Chain



Eventually, some miner creates a new block attached to 2B (row *c*). Because all miners must work at the highest height, those miners working on finding a successor to 1A stop that work. All miners are now working on creating a block to attach to the accepted block 2. At row *d* in Figure 6, one miner has successfully created and attached a block at height 3, and broadcasts this update to the network. All of the miners abandon their work at height two and now try to attach a block to the new block 4.

Next, a miner adds a block at height 4 and broadcasts it to the network (row *e*). Other miners, as soon as they receive this information, begin to work at block 4. However, at least one miner, before it receives this update, creates a block at height 4, creating a fork in the chain (row *f*), as happened back at row *c* in the figure. This situation creates a race condition that may continue. It is possible that both forks of the chain solve another block at about the same time (row *g*). In this example, the miners working on 5B solve a block, first adding a new block 6 (row *g*). This new chain, with block 6, is broadcast to all users and miners on the network. With block 6 in place, users are assured the blocks 4A and 5A are "locked in" to the blockchain. And miners who were working to add a block 6 realize they have lost the race. Now all miners begin working to try to append a new block after block 6. This activity continues as the chain grows, with occasional forks that are eventually discarded.

Confirming Transactions

As a miner is collecting transactions, it validates each one. The nature of the validation depends on the application but generally it depends on the use of public-key cryptography to authenticate the parties to the transaction and assure the integrity of the content of the transaction record[10]. The miner then assembles its current pool of validated transactions into a block. When the block is established as the next block in the chain, it is referred to as a *confirmation*. If there is a fork in the chain, then this confirmation is only provisional until the fork is resolved.

The deeper a block is embedded in a chain (that is, farthest from the current height of the change) the more difficult it would be for an adversary to alter the block. Thus, in any given application, a user of the distributed ledger can decide how many confirmations to wait for before acting with full confidence in a particular ledger entry.

Scalability

A blockchain in active use grows over time and never shrinks, raising the question of the scalability of a blockchain application. For example, Bitcoin allows a maximum block size of 2 MB and as of November 6, 2017, Bitcoin blockchain activity had the following characteristics (`https://blockchain.info`):

- Blockchain size (total size of all block headers and transactions, not including database indexes): 140.295 GB
- Average block size: 1.03 MB

- Transactions per day (most recent day): 333,161
- Aggregate size of transactions waiting to be confirmed: 40.31 MB

To perform all the Bitcoin functions and store the entire blockchain requires considerable processing and memory resources. For many blockchain applications, however, it is not necessary for all users to perform all the blockchain tasks, which include mining management, *Peer-to-Peer* (P2P) network communication and blockchain management, key management, and virtual asset management. For many blockchain applications, systems can be configured that provide only a subset of the tasks of a full implementation, with the handling of public-private key pairs as the most common core feature.

The authors of [11] define five categories of configuration:

- *Basic Client:* A client that runs on a user-controlled device and can perform key management operations, but cannot perform any P2P network communication. It is not a stand-alone solution. Examples include some dedicated hardware clients/wallets and cold-storage (offline storage) clients that require a second online device for transaction processing.
- *Thin Client:* A client that runs on a user-controlled device and can perform key management operations. It performs some P2P tasks related to network communication and blockchain verification but does not keep a copy of the full blockchain.
- *Thick Client:* A client that runs on a user-controlled device and performs all P2P tasks related to network communication and blockchain verification, keeps a copy of the full blockchain, and can perform all key management-related operations. This type of client is sometimes referred to as a *full node*.
- *Fully Functional Basic Client:* A node that performs all of the functions of a thick client, and executes the mining algorithm.
- *Hosted Client:* A client that does not run on a user-controlled device and all tasks are performed by a trusted third party on behalf of the user. This type of client is sometimes referred to as *hosted* or *web client/wallet*. In this case, it is not relevant whether key management is handled in the browser (for example, via JavaScript) because this requirement would in turn require users to download and verify the script code from the website of the third party every time they want to use it.

Depending on the blockchain application, even a full client may not need to store the full chain going back to the genesis block. That task can be reserved for a few archival nodes. The archival nodes can be used to bootstrap fully validating nodes from the beginning but are otherwise not active.

An example of a thin client is the *Simple Payment Verification* (SVP) client used in the Bitcoin application[12]. The majority of nodes on the Bitcoin network are SVP clients.

An SVP client stores only the portions of a blockchain needed to verify specific transactions of interest to this client. The node downloads the block headers and transactions that represent payments to its addresses. An SPV node doesn't have the security level of a fully validating node. Since the node has block headers, it can check that the blocks were difficult to mine, but it can't check to see that every transaction included in a block is actually valid because it doesn't have the transaction history and doesn't know the set of unspent transactions outputs. SPV nodes can validate only the transactions that actually affect them. The SPV nodes trust the fully validating nodes to have validated all the other transactions that are out there. The cost savings of being an SPV node are substantial. The block headers are only about 0.1% the size of the block chain. So instead of storing tens of gigabytes, the SPV node stores only a few tens of megabytes. Even a smartphone can easily act as an SPV node in the Bitcoin network.

Blockchain Types

Broadly speaking, there are three types of blockchains[13]. A *Public Blockchain* can be accessed and mined by anyone with Internet access. Access includes not only reading but also posting transactions, and they will be included if they are valid. Nodes participating in a public blockchain network do not have to obtain permission to access the ledger or add transactions. These blockchains are generally considered to be fully decentralized. Public blockchains have the benefit of information transparency and auditability, but they sacrifice information privacy.

A *Consortium Blockchain* is used across multiple organizations. The consensus process is controlled by authorized nodes. For example, one might imagine a consortium of 15 financial institutions, each of which operates a node and of which 10 must sign every block in order for the block to be valid. The right to read the blockchain may be public or restricted to the participants, and there are also hybrid variations such as the root hashes of the blocks being public together with an *Application Programming Interface* (API) that allows members of the public to make a limited number of queries and get back cryptographic proofs of some parts of the blockchain state. These blockchains may be considered partially decentralized.

A *Fully Private Blockchain*, or *Permissioned Blockchain,* limits write permissions to within a single organization that owns the blockchain. Read permissions may be public or restricted to an arbitrary extent. Likely applications include database management and auditing internal to a single company, so public readability may not be necessary in many cases at all, though in other cases public auditability is desired.

Currently, and projected for the foreseeable future, the majority of blockchain applications by market share are public. Most of the remainder are fully private[14].

Bitcoin

The original application of blockchain, for which it was invented, is *Bitcoin*. Bitcoin is perhaps the most widely used alternative (non-state-issued) currency in the world. Bitcoin is a digital currency scheme[15]. The network of miners literally creates money out of computer processing cycles. Currency within the system is given value (as it is in any money system) by its scarcity; in this system, the scarcity is created by requiring that money be processed by computationally intensive procedures. Having a great deal of computational power enables a miner to create Bitcoin value more quickly.

Blockchain provides the ledger for recording all of the digital currency transactions. Each transaction is potential only until it is recorded in a block that is accepted as valid and added to the chain. Recording requires the cooperative effort of the miners to achieve. As in incentive, miners are paid in Bitcoins for successfully adding a block to the blockchain.

Other Blockchain Applications

Great interest is being shown in applying blockchain technology to a wide variety of commercial and government applications. The following applications are listed in[16]:

- *Nasdaq* is using its Linq blockchain technology to complete and record private securities transactions.
- *Depository Trust & Clearing Corporation,* working with market participants and technology firm Axoni, is managing post-trade events for credit default swaps.
- *Factom* is providing blockchain technology for the Honduran land registry project. The focus is data security.
- *Everledger*'s focus is on the identity and legitimacy of objects. Blockchain works well here because its history cannot be changed and it enables trust by consensus. The company's initial work provides a distributed ledger of diamond ownership and transaction history verification for owners, insurance companies, claimants, and law enforcement agencies. The system assists with prevention of fraud in the supply chain, but also helps consumers decide whether to buy particular diamonds. The ultimate goal is to track diamonds from mine to market, so that consumers can see if correct duties and taxes have been paid and whether a diamond is a "blood diamond" that has been mined and traded in a war zone and contributed to human atrocity.

Blockchain technology has also caught the interest of numerous government agencies dealing with national security and homeland security, including *Defense Advanced Research Projects Agency* (DARPA) and the U.S. Air Force. The *Department of Homeland Security* (DHS) has awarded contracts for five projects that will use distributed ledger technology to develop new solutions for identity management and privacy protection[17]:

- *Digital Bazaar* is developing a Linked Data ledger format and architecture to demonstrate how to publish identity credentials.
- *Respect Network Corporation* is developing a decentralized registry and discovery service to integrate with the public blockchain.
- *Narf Industries* is developing an identity management solution built on a permission-less blockchain, with a focus on confidentiality (with selective information disclosure), integrity, availability, non-DHS repudiation, provenance, and pseudo-anonymity.
- *Xcelerate Solutions* is researching blockchain solutions to enable users to establish and maintain trusted identity transactions with public and private organizations.
- *Factom* is studying possible blockchain-based advancements for the security of digital identities for the *Internet of Things* (IoT). The project will create an identity log that captures the identification of a device, who manufactured it, lists of available updates, known security issues, and granted authorities while adding the dimension of time for added security. The goal is to limit would-be hackers' abilities to corrupt the past records for a device, making it more difficult to spoof.

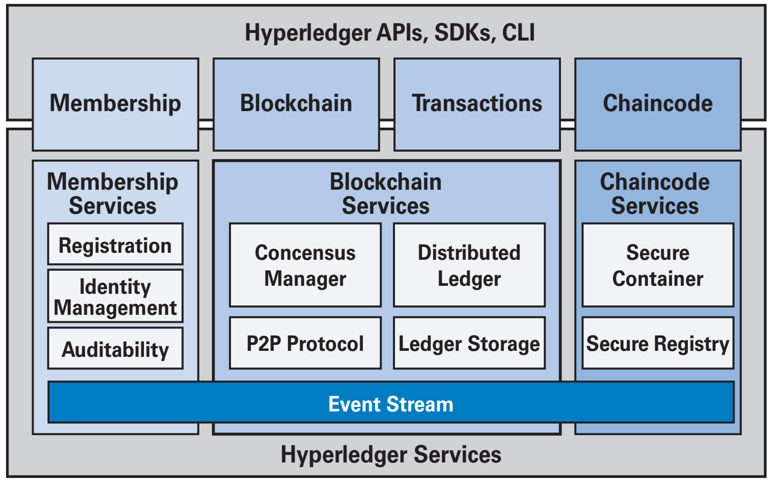
Another interesting development, one that indicates the growing and widespread popularity of the blockchain technology, is the *Initial Coin Offering* (ICO). With the ICO model, instead of selling ownership shares to investors to finance the start of the company, the startup sells digital coins, or tokens, that have value within the application or service the company offers. Sales of ICO tokens exceeded US$250 million in 2016 and are estimated to exceed US$1 billion in 2017[18].

Open-Source Blockchain

In 2016, the Linux Foundation, a nonprofit that champions open-source technologies, announced the *Hyperledger* project, an effort to create an enterprise-grade distributed blockchain ledger framework (`https://www.hyperledger.org`)[19, 20]. Participants in the group include R3, Cisco Systems, IBM, Intel, and VMware, among others. The objective of this project is to develop a standardized, production-grade digital ledger fabric. The project focuses on identifying and addressing important features for an enterprise-class, cross-industry open standard for distributed ledgers that can transform the way business transactions are conducted globally.

Figure 7 illustrates the current Hyperledger reference architecture within which open-source code is being developed.

Figure 7: Hyperledger Reference Architecture



Four main elements make up a Hyperledger-based application:

- *Membership:* Deals with registering, identifying, and auditing the activity of the peers who will use this particular ledger. The system distinguishes between two kinds of peers. A *validating peer* is a node on the network responsible for running consensus, validating transactions, and maintaining the ledger. A *non-validating peer* is a node that functions as a proxy to connect clients (issuing transactions) to validating peers.
- *Blockchain:* Consists of all the functions associated with building, storing, and providing access to a blockchain ledger.
- *Chaincode:* Implemented in Go, Chaincode is the realization of a smart contract. Each chaincode is encapsulated in a Docker container.
- *Transactions:* Examples of transaction types include the following: A *deploy* transaction takes a chaincode as a parameter; the chaincode is installed on the peers and is ready to be invoked. An *invoke* transaction invokes a transaction of a particular chaincode that has been installed earlier through a deploy transaction; the arguments are specific to the type of transaction. A *query* transaction returns an entry of the state directly from reading the peer's persistent state.

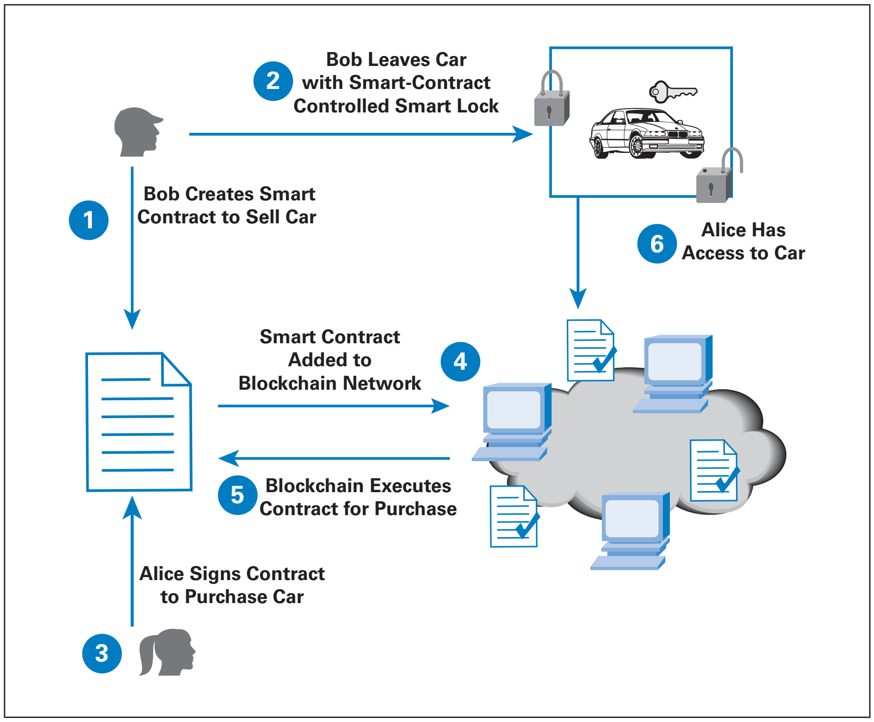
Smart Contracts

Smart Contracts (also called *Self-Executing Contracts, Blockchain Contracts,* or *Digital Contracts*) are computer programs that act as agreements, in which the terms of the agreement can be preprogrammed with the ability to self-execute and self-enforce itself. The main goal of a smart contract is to enable two anonymous parties to trade and do business with each other, usually over the Internet, without the need for a middleman.

The concept of smart contracts predates blockchain technology, but it is blockchain that has enabled the sudden growth in the use of smart contracts. One of the most prominent platforms for blockchain-based smart contracts is the open-source platform *Ethereum*[21].

An example of the use of smart contracts is shown in Figure 8[22].

Figure 8: Smart Contract Example



The steps involved follow:

1. Bob creates a digital contract to sell his car. He identifies himself with his blockchain address (757382), which is his public key, uses a smart contract to define the terms of the sale, and signs the contract with his private key. The terms might read as follows:

```
IF $20,000 is sent to my account number 757382
THEN Transfer car ID 73849Z to account number that transferred the money
     Grant smart lock access to account number that transferred the money
```

   That English language description corresponds to code embedded in the digital contract. When the contract is added to the blockchain ledger, the code is automatically executed.

2. Bob leaves his car and car key in a garage locked with a smart lock controlled by the smart contract. The car has its own blockchain address 73849Z, which is a public key stored on the blockchain.

3. Alice wants to buy the car and searches for a suitable contract via a web browser. She finds Bob's car listed and signs the contract with her private key, which triggers an automatic transfer of $20,000 from her blockchain address (389157), which is her public key, to Bob's blockchain address 757382.
4. The signed smart contract is verified by each node in the blockchain network to verify that Bob is the owner of the car and that Alice has sufficient funds for the purchase.
5. If the network verifies the conditions, Alice automatically gets the access code to the smart lock for the garage (encrypted with Alice's public key), Alice is registered as the new owner, and $20,000 is transferred to Bob.
6. Alice can obtain the access code using her private key and then use the access code to pick up her car.

The whole process is distributed, automated, and does not require a central authority. In general, any blockchain-based smart contract employs the following steps:

1. A contract is defined. For some applications, there is a pre-defined contract specifying the terms of the contract and conditions for execution.
2. An event triggers the execution of the contract. An event could be the initiation of a transaction or the receipt of information.
3. When the contract is added to the blockchain ledger, the contract is executed, a process that typically involves movement of some value based on conditions met.

4a. For digital assets on the blockchain, such as cryptocurrency, accounts are automatically settled.

4b. For assets that are not part of the blockchain, such as stocks, changes to accounts in the ledger will match settlement instructions off the blockchain.

The smart contract model is very flexible and can be used in a wide variety of applications; some of them are listed in Table 2[23] on the following page.

Table 2: Blockchain Use Cases

Use Case	Description
Trade Clearing and Settlement	Manages approval workflows between counterparties, calculates trade settlement amounts, and transfers funds automatically
Coupon Payments	Automatically calculates and pays periodic coupon payments and returns principle upon bond expiration
Insurance Claims Processing	Performs error checking, routing, and approval workflows, and calculates payout based on the type of claim and underlying policy
Micro-insurance	Calculates and transfers micropayments based on usage data from an IoT-enabled device (for example, pay-as-you-go automotive insurance)
Electronic Medical Records	Provides transfer and/or access to medical records upon multi-signature approvals between patients and providers
Population Health Data Access	Grants health researchers access to certain health information; micropayments are automatically transferred to the patient for participation
Personal Health Tracking	Tracks patients' health-related actions through IoT devices and automatically generates rewards based on specific milestones
Royalty Distribution	Calculates and distributes royalty payments to artists and other associated parties according to the contract
Autonomous Electric Vehicle Charging Station	Processes a deposit, enables the charging station, and returns remaining funds when complete
Record Keeping	Updates private company share registries and capitalization table records, and distributes shareholder communications
Supply Chain and Trade Finance Documentation	Transfers payments upon multi-signature approval for letters of credit and issues port payments upon custody change for bills of lading
Product Provenance and History	Facilitates chain-of-custody process for products in the supply chain where the party in custody is able to log evidence about the product
Peer-to-Peer Transacting	Matches parties and transfer payments automatically for various peer-to-peer applications: lending, insurance, energy credits, etc.
Voting	Validates voter criteria, logs vote to the blockchain, and initiates specific actions as a result of the majority vote

Summary

Four elements characterize blockchain:

Blockchain is a Replicated Ledger. The ledger provides a history of all transactions that is immutable and is changed only by appending at the newest end of the linear chain of blocks that implements the ledger. The ledger is distributed and readable by all participants.

Blockchain operates by Consensus. Consensus is implemented by means of a shared, decentralized, peer-to-peer protocol. This shared control of the blockchain tolerates disruption, in that from time to time there may be temporary forks in the otherwise linear chain. The consensus mechanism is a means for validating transactions.

Fundamental to the operation of blockchain is *Cryptography.* Various cryptographic algorithms ensure the integrity of the ledger, the authenticity of transactions, the privacy of transactions, and the identity of participants.

Finally, blockchain is a versatile framework for implementing *Business Logic* that is embedded in the ledger. This logic is application-dependent and is reflected in the format and content of the transactions.

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