The Internet Computer for Geeks

(v1.4)

The DFINITY Team*

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Abstract

Smart contracts are a new form of software that will revolutionize how software is written, IT systems are maintained, and applications and whole businesses are built. Smart contracts are composable and autonomous pieces of software that run on decentralized blockchains, which makes them tamperproof and unstoppable. In this paper, we describe the Internet Computer (IC), which is a radical new design of blockchain that unleashes the full potential of smart contracts, overcoming the limitations of smart contracts on traditional blockchains with respect to speed, storage costs, and computational capacity. This allows smart contracts for the first time to implement fully decentralized applications that are hosted end to end on blockchain. The IC consists of a set of cryptographic protocols that connects independently operated nodes into a collection of blockchains. These blockchains host and execute "canisters", the IC's form of smart contracts. Canisters can store data, perform very general computations on that data, and provide a complete technology stack, serving web pages directly to end users. Computational and storage costs are covered by a "reverse-gas model", where canister developers pre-pay costs in cycles that are obtained from ICP, the native token of the IC. ICP tokens are also used for governance: the IC is governed by a decentralized autonomous organization, or DAO, which, among other things, determines changes to the topology of the network and upgrades to the protocol.

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1 Introduction

1.1 Unleashing smart contracts

Because of their unique features, smart contracts are the key enabler of Web3, the new approach to the web where applications are fully controlled by their users and run on decentralized blockchain platforms. Such decentralized applications (dapps) are typically tokenized, meaning tokens are distributed to users as rewards for participating in the dapps. Participation can come in many different forms, ranging from moderating and providing content to governing a dapp and to creating and maintaining a dapp. Usually, tokens can also be bought on exchanges; indeed, selling tokens is a common way to finance dapp development. Finally, tokens are also used as a form of payment for the services or contents a dapp offers. Smart contracts running on today's blockchain platforms, including all the

*`https://dfinity.org/foundation/`; contact author: Yvonne-Anne Pignolet, `yap@dfinity.org`.

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popular ones (such as Ethereum), suffer from many limitations, such as high transaction and storage costs, slow computational speed, and the inability to serve frontends to users. As a result, many popular blockchain applications are not fully decentralized but are hybrids where most of the application is hosted on traditional cloud platforms and call out to smart contracts on a blockchain for a small part of their overall functionality. Unfortunately, this renders such applications non-decentralized, and opens them to many of the drawbacks of traditional cloud-hosted applications, such as being at the mercy of cloud providers, and being vulnerable to many single points of failure.

The **Internet Computer (IC)** is a new platform for executing **smart contracts**. Here, we use the term "smart contract" in a very broad sense: a *general-purpose*, *tamperproof* computer program whose execution is performed *autonomously* on a *decentralized public network*.

- By *general purpose*, we mean that the class of smart contract programs is Turing complete (i.e., anything computable can be computed by a smart contract).
- By *tamperproof*, we mean that the instructions of the program are carried out faithfully and that intermediate and final results are accurately stored and/or transmitted.
- By *autonomous*, we mean that a smart contract is executed automatically by the network, without the need for any action on the part of any individual.
- By a *decentralized public network*, we mean a network of computers that is publicly accessible, geographically distributed, and not under the control of a small number of individuals or organizations.

In addition, smart contracts

- are *composable*, meaning that they may interact with one another, and
- support *tokenization*, meaning that they may use and trade digital tokens.

Compared to existing smart contract platforms, the IC is designed to:

- be *more cost effective*, in particular, allowing applications to compute and store data at a fraction of the cost of previous platforms;
- provide *higher throughput and lower latency* for processing smart contract transactions;
- be *more scalable*, in particular, the IC can process unbounded volumes of smart contract data and computation natively because it can grow in capacity by adding more nodes to the network.

Another property that smart contracts may have is *immutability*, which means that, once deployed, the code of a smart contract cannot be changed by a party unilaterally. While this feature is essential in some applications, it is not required in all applications, and can also be problematic if a smart contract has a bug that needs to be fixed. The IC allows a range of mutability policies for smart contracts, ranging from purely immutable to unilaterally upgradable, with other options in between.

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In addition to providing a smart contract platform, the IC is designed to act as a *complete technology stack*, such that systems and services can be built that run entirely on the IC. In particular, smart contracts on the IC can service HTTP requests created by end users, so that smart contracts can directly serve interactive web experiences. This means that systems and services can be created without relying on corporate cloud hosting services or private servers, thus providing all of the benefits of smart contracts in a true end-to-end fashion.

Realizing the vision of Web3. For end-users, accessing IC-based services is largely transparent. Their personal data is more secure than when accessing applications on a public or private cloud, but the experience of interacting with the application is the same.

For the people creating and managing those IC-based services, however, the IC eliminates many of the costs, risks, and complexities associated with developing and deploying modern applications and microservices. For example, the IC platform provides an alternative to the consolidation driven by large technology companies that are monopolizing the Internet. In addition, its secure protocol guarantees reliable message delivery, transparent accountability, and resilience without relying on firewalls, backup facilities, load balancing services, or failover orchestration.

Building the IC is about restoring the Internet to its open, innovative, and creative roots — in other words, *to realize the vision of Web3*. To focus on a few specific examples, the IC does the following:

- Supports interoperability, shared functions, permanent APIs, and ownerless applications, all of which reduce platform risk and encourages innovation and collaboration.
- Persists data automatically in memory, which eliminates the need for database servers and storage management, improves computational efficiency, and simplifies software development.
- Simplifies the technology stack that IT organizations need to integrate and manage, which improves operational efficiency

1.2 High level view of the Internet Computer

To a first approximation, the IC is a network of interacting **replicated state machines**. The notion of a replicated state machine is a fairly standard concept in distributed systems [Sch90], but we give a brief introduction here, beginning with the notion of a *state machine*.

A **state machine** is a particular model of computation. Such a machine maintains a **state**, which corresponds to main memory or other forms of data storage in an ordinary computer. Such a machine executes in discrete **rounds**: in each round, it takes an **input**, applies a **state transition function** to the *input* and the *current state*, obtaining an **output** and a *new state*. The *new state* becomes the *current state* in the next round.

The state transition function of the IC is a **universal function**, meaning that some of the inputs and data stored in the state may be arbitrary **programs** which act on other inputs and data. Thus, such a state machine represents a general (i.e., Turing complete) model of computation.

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To achieve **fault tolerance**, the state machine may be *replicated*. A *replicated state machine* comprises a **subnet** of **replica**s, each of which is running a copy of the same state machine. A subnet should continue to function — and to function correctly — even if some replicas are **faulty**.

It is essential that each replica in a subnet processes the same inputs in the same order. To achieve this, the replicas in a subnet must run a **consensus protocol** [Fis83], which ensures that all replicas in a subnet process inputs in the same order. Therefore, the internal state of each replica will evolve over time in exactly the same way, and each replica will produce exactly the same sequence of outputs. Note that an input to a replicated state machine on the IC may be an input generated by an external user, or an output generated by another replicated state machine. Similarly, an output of a replicated state machine may be either an output directed to an external user, or an input to another replicated state machine.

1.3 Fault Models

In the distributed systems area of computer science, one typically considers two types of replica failures: **crash faults** and **Byzantine faults**. A **crash fault** occurs when a replica abruptly stops and does not resume. **Byzantine faults** are failures in which a replica may deviate in an arbitrary way from its prescribed protocol. Moreover, with Byzantine faults, one or possibly several replicas may be directly under the control of a malicious adversary who may coordinate the behavior of these replicas. Of the two types of faults, Byzantine faults are potentially far more disruptive.

Protocols for consensus and for realizing replicated state machines typically make assumptions about **how many** replicas may be faulty and **to what degree** (crash or Byzantine) they may be faulty. In the IC, the assumption is that if a given subnet has n replicas, then less than $n/3$ of these replicas are faulty and these faults may be Byzantine. (Note that the different subnets in the IC may have different sizes.)

1.4 Communication Models

Protocols for consensus and for implementing replicated state machines also typically make assumptions about the **communication model**, which characterizes the ability of an adversary to delay the delivery of messages between replicas. At opposite ends of the spectrum, we have the following models:

- In the **synchronous model**, there exists some known finite time bound δ, such that for any message sent, it will be delivered in less than time δ.
- In the **asynchronous model**, for any message sent, the adversary can delay its delivery by any finite amount of time, so that there is no bound on the time to deliver a message.

Since the replicas in an IC-subnet are typically distributed around the globe, the synchronous communication model would be highly unrealistic. Indeed, an attacker could

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compromise the correct behavior of the protocol by delaying honest replicas or the communication between them. Such an attack is generally easier to mount than gaining control over and corrupting an honest replica.

In the setting of a globally distributed subnet, the most realistic and robust model is the asynchronous model. Unfortunately, there are no known consensus protocols in this model that are truly practical (more recent asynchronous consensus protocols, as in [MXC+16], attain reasonable throughput, but not very good latency). So like most other practical Byzantine fault tolerant systems that do not rely on synchronous communication (e.g., [CL99, BKM18, YMR+18]), the IC opts for a compromise: a **partial synchrony** communication model [DLS88]. Such partial synchrony models can be formulated in various ways. The partial synchrony assumption used by the IC says, roughly speaking, that for each subnet, communication among replicas in that subnet is periodically synchronous for short intervals of time; moreover, the synchrony bound δ does not need to be known in advance. This partial synchrony assumption is only needed to ensure that the consensus protocol makes progress (the so-called liveness property). The partial synchrony assumption is not needed to ensure correct behavior of consensus (the so-called safety property), nor is it needed anywhere else in the IC protocol stack.

Under the assumption of partial synchrony and Byzantine faults, it is known that our bound of $f < n/3$ on the number of faults is optimal.

1.5 Permission Models

The earliest protocols for consensus (e.g., PBFT [CL99]) were **permissioned**, in the sense that the replicas comprising a replicated state machine are governed by a centralized organization, which determines which entities provide replicas, the topology of the network, and possibly also implements some kind of centralized public-key infrastructure. Permissioned consensus protocols are typically the most efficient, and while they do avoid a single point of failure, the centralized governance is undesirable for certain applications, and it is antithetical to the spirit of the burgeoning Web3 era.

More recently, we have seen the rise of **permissionless** consensus protocols, such as Bitcoin [Nak08], Ethereum [But13], and Algorand [GHM+17]. Such protocols are based on a **blockchain** and either a **proof of work (PoW)** (e.g., Bitcoin, Ethereum prior to v2.0) or a **proof of stake (PoS)** (e.g., Algorand, Ethereum v2.0) . While such protocols are completely decentralized, they are much less efficient than permissioned protocols. We also point out that, as observed in [PSS17], PoW-based consensus protocols such as Bitcoin cannot guarantee correctness (i.e., safety) in an asynchronous communication network.

The IC's permission model is a **hybrid model**, obtaining the efficiency of a permissioned protocol while offering many of the benefits of a decentralized PoS protocol. This hybrid model is called a **DAO-controlled network** and (roughly speaking) works as follows: each subnet runs a permissioned consensus protocol, but a **decentralized autonomous organization (DAO)** determines which entities provide replicas, configures the topology of the network, provides a public-key infrastructure, and controls which version of the protocol is deployed to the replicas. The IC's DAO is called the **network nervous system (NNS)**, and is based on a PoS, so that all decisions taken by the NNS are made by community members whose voting power is determined by how much of the IC's native governance

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token they have staked in the NNS (see Section 1.8 for more on this token). Through this PoS-based governance system, new subnets can be created, replicas may be added to or removed from existing subnets, software updates may be deployed, and other modifications to the IC may be effected. The NNS is itself a replicated state machine, which (like any other) runs on a particular subnet whose membership is determined via the same PoS-based governance system. The NNS maintains a database called the **registry**, which keeps track of the topology of the IC: which replicas belong to which subnets, the public keys of the replicas, and so on (see Section 1.10 for a few more details on the NNS).

Thus, one sees that the IC's DAO-controlled network allows the IC to achieve many of the practical benefits of a permissioned network (in terms of more efficient consensus), while maintaining many of the benefits of a decentralized network (with governance controlled by a DAO).

The replicas running the IC protocol are hosted on servers in geographically distributed, independently operated data centers. This also bolsters the security and decentralized nature of the IC.

1.6 Chain-key cryptography

The IC's consensus protocol does, in fact, use a blockchain, but it also uses public-key cryptography, specifically, digital signatures: the registry maintained by the NNS is used to bind public keys to replicas and subnets as a whole. This enables a unique and powerful collection of technologies that we call **chain-key cryptography**, which has several components.

1.6.1 Threshold signatures

The first component of chain-key cryptography is **threshold signatures**: this is a well established cryptographic technique that allows a subnet to have a public signature-verification key whose corresponding secret signing key is split into **shares**, which are distributed among all of the replicas in a subnet in such a way that the shares held by the corrupt replicas do not let them forge any signatures, while the shares held by the honest replicas allow the subnet to generate signatures consistent with the policies and protocols of the IC.

One critical application of these threshold signatures is that

> *an individual output of one subnet may be verified by another subnet or external user by simply validating a digital signature with respect to the public signature-verification key of the (first) subnet.*

Note that the public signature-verification key for a subnet may be obtained from the NNS — this public signature-verification key remains constant over the lifetime of a subnet (even as the membership of a subnet may change over that lifetime). This stands in contrast to many non-scalable blockchain-based protocols, which require the entire blockchain to be validated in order to validate any single output.

As we will see, these threshold signatures have a number of other applications within the IC. One such application is to give each replica in a subnet access to unpredictable pseudorandom bits (derived from such signatures). This is the basis for the **Random Beacon** used in consensus and the **Random Tape** used in execution.

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In order to securely deploy threshold signatures, the IC uses an innovative **distributed key generation (DKG)** protocol that constructs a public signature-verification key and provisions each replica with a share of the corresponding secret signing key, and works within our fault and communication model.

1.6.2 Chain-evolution technology

Chain-key cryptography also includes a sophisticated collection of technologies for robustly and securely maintaining a blockchain based replicated state machine over time, which together form what we call **chain-evolution technology**. Each subnet operates in **epochs** of many rounds (typically on the order of a few hundreds of rounds). Using threshold signatures and a number of other techniques, chain-evolution technology implements many essential maintenance activities that are executed periodically with a cadence that is tied to epochs:

Garbage collection: At the end of each epoch, all inputs that have been processed, and all consensus-level protocol messages needed to order those inputs, may safely be purged from the memory of each replica. This is essential in keeping the storage requirements for the replicas from growing without bound. This is in contrast to many non-scalable blockchain-based protocols, where the entire blockchain from the genesis block must be stored.

Fast forwarding: If a replica in a subnet falls very far behind its peers (because it is down or disconnected from the network for a long time), or a new replica is added to a subnet, it can be *fast forwarded* to the beginning of the most recent epoch, without having to run the consensus protocol and process all of the inputs up to that point. This is in contrast to many non-scalable blockchain-based protocols, where the entire blockchain from the genesis block must be processed.

Subnet membership changes: The membership of the subnet (as determined by the NNS, see Section 1.5) may change over time. This can only happen at an epoch boundary, and needs to be done with care to ensure consistent and correct behavior.

Pro-active resharing of secrets: We mentioned above in Section 1.6.1 how the IC uses chain-key cryptography — specifically, threshold signatures — for output verification. This is based on **secret sharing**, which avoids any single point of failure by splitting up a secret (in this case, a secret signing key) into shares that are stored among the replicas. At the beginning of each epoch, these shares are **pro-actively reshared**. This achieves two goals:

- When the membership of a subnet changes, the resharing will ensure that any new members have an appropriate share of the secret, while any replicas that are no longer members no longer have a share of the secret.
- If a small number of shares are leaked to an attacker in any one epoch, or even in *every* epoch, those shares will not do an attacker any good.

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Protocol upgrades: When the IC protocol itself needs to be upgraded, to fix bugs or add new features, this can be done automatically using a special protocol at the beginning of an epoch.

1.7 Execution Models

As already mentioned, replicated state machines in the IC can execute arbitrary programs. The basic computational unit in the IC is called a **canister**, which is roughly the same as the notion of a *process*, in that it comprises both a *program* and its *state* (which changes over time).

Canister programs are encoded in **WebAssembly**, or **Wasm** for short, which is a binary instruction format for a stack-based virtual machine. Wasm is an open standard.[1] While it was initially designed to enable high-performance applications on web pages, it is actually very well suited to general-purpose computation.

The IC provides a run-time environment for executing Wasm programs in a canister, and to communicate with other canisters and external users (via message passing). While, in principle, one can write a canister program in any language that may be compiled to Wasm, a language called **Motoko** has been designed that is well aligned with the operational semantics of the IC. Motoko is a strongly typed, *actor-based*[2] programming language with built-in support for *orthogonal persistence*[3] and *asynchronous message passing*. Orthogonal persistence simply means that all memory maintained by a canister is automatically persisted (i.e., it does not have to be written to a file). Motoko has a number of productivity and safety features, including automatic memory management, generics, type inference, pattern matching, and both arbitrary and fixed-precision arithmetic.

In addition to Motoko, the IC also provides a messaging interface definition language and wire format called **Candid**, for typed, high-level, and cross-language interoperability. This allows any two canisters, even if written in different high-level languages, to easily communicate with one another.

To fully support canister development in any given programming language, besides a Wasm compiler for that language, certain run-time support must also be provided. At the present time, in addition to Motoko, the IC also fully supports canister development in the Rust programming language.

1.8 Utility token

The IC makes use of a **utility token** called **ICP**. This token is used for the following functions:

Staking in the NNS: As already discussed in Section 1.5, ICP tokens may be *staked* in the NNS to acquire voting rights so as to participate in the DAO that controls the IC network. Users that have ICP tokens staked in the NNS and who participate in

[1] See `https://webassembly.org/`.

[2] See `https://en.wikipedia.org/wiki/Actor_model`.

[3] See `https://en.wikipedia.org/wiki/Persistence_(computer_science)#Orthogonal_or_transparent_persistence`.

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the NNS governance also receive *newly minted* ICP tokens as a *voting reward*. The amount of the award is determined by policies established and enforced by the NNS.

Conversion to Cycles: ICP is used to pay for the usage of the IC. More specifically, ICP tokens can be converted to **cycles** (i.e., *burned*), and these cycles are used to pay for creating canisters (see Section 1.7) and for the resources that canisters use (storage, CPU, and bandwidth). The rate at which ICP is converted to cycles is determined by the NNS.

Payment to Node Providers: ICP tokens are used to pay the node providers—these are the entities that own and operate the computing nodes that host the replicas that make up the IC. At regular intervals (currently monthly), the NNS decides on the number of *newly minted* tokens that each node provider should receive, and sends the tokens to the node provider's account. Payment of tokens is conditioned on providing reliable service to the IC, according to specific policies established and enforced by the NNS.

1.9 Boundary Nodes

Boundary nodes provide the network edge services of the IC. In particular, they offer

- clearly defined entry points to the IC,
- denial of service protection for the IC,
- seamless access to the IC from legacy clients (e.g., web browsers).

To facilitate seamless access to the IC from a legacy client, boundary nodes provide functionality to translate a standard HTTPS request from a user to an ingress message directed toward a canister on the IC, and then route this ingress message to specific replicas on the subnet where this canister resides. Furthermore, boundary nodes offer additional services to improve the user experience: caching, load balancing, rate limiting, and the ability for legacy clients to authenticate responses from the IC.

A canister is identified by a URL on the `ic0.app` domain. Initially, a legacy client looks up the corresponding DNS record for the URL, obtains an IP address of a boundary node, and then sends an initial HTTPS request to this address. The boundary node returns a javascript-based "service worker" that will be executed in the legacy client. After this, all interactions between the legacy client and the boundary node will be done via this service worker.

One of the essential tasks carried out by the service worker is to authenticate responses from the IC using chain-key cryptography (see Section 1.6). To do this, the public verification key for the NNS is hard-coded in the service worker.

The boundary node itself is responsible for routing requests to a replica on the subnet on which the specified canister is hosted. The information needed to perform this routing is obtained by the boundary node from the NNS. The boundary node keeps a list with replicas that provide timely replies and selects a random replica from this list.

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All communication between legacy clients and boundary nodes and between boundary nodes and replicas is secured via TLS.[4]

In addition to legacy clients, it is also possible to interact with boundary nodes using "IC native" clients, which already include the service-worker logic, and do not need to retrieve the service worker program from the boundary node.

Just as for replicas, the deployment and configuration of boundary nodes is controlled by the NNS.

1.10 More details of the NNS

As already mentioned in Section 1.5, the network nervous system (NNS) is an algorithmic governance system that controls the IC. It is realized by a set of canisters on a special **system subnet**. This subnet is like any other subnet, but is configured somewhat differently (as one example, canisters on the system subnet are not charged for the cycles they use).

Some of the most relevant NNS canisters are

- the **registry canister**, which stores the configuration of the IC, i.e., which replicas belong to which subnet, the public keys associated with subnets and individual replicas, and so on.
- the **governance canister**, which manages the decision making and voting on how the IC should be evolved, and
- the **ledger canister**, which keeps track of the users' ICP utility token accounts and the transactions between them.

1.10.1 Decision making on the NNS

Anyone can participate in NNS governance by staking ICP tokens in so-called **neurons**. Neuron holders can then suggest and vote on **proposals**, which are suggestions on how the IC should be changed, e.g., how the subnet topology or the protocol should be changed. The neurons' voting power for decision making is based on proof of stake. Intuitively, neurons with more staked ICP tokens have more voting power. However, the voting power also depends on some other neuron characteristics, e.g., more voting power is given to neuron holders that are committed to keep their tokens staked for a longer period of time.

Each proposal has a determined voting period. A proposal is **adopted** if at the voting period's end, a simple majority of the total voting power has voted in favor of the proposal and these Yes-votes constitute a given quorum (currently 3%) of the total voting power. Otherwise, the proposal is **rejected**. In addition, a proposal is adopted or rejected at any point if an absolute majority (more than half of the total voting power) is in favor or against the proposal, respectively.

If a proposal is adopted, the governance canister automatically executes the decision. For example, if a proposal suggests changing the network topology and is adopted, the governance canister automatically updates the registry with the new configurations.

[4] See `https://en.wikipedia.org/wiki/Transport_Layer_Security`.

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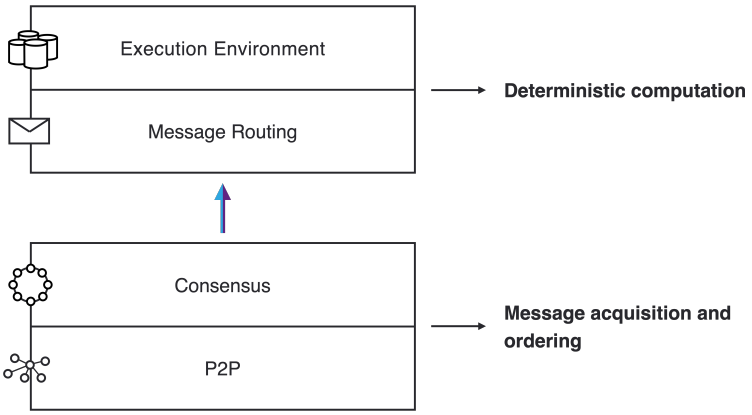


Figure 1: The layers of the Internet Computer Protocol

1.11 Advanced Features

The architecture of the IC enables functionality to bring the advantages of tokenized DAO governance to any dapp running on the IC as well as direct interaction with other chains.

DAO-controlled canisters. Just like the overall configuration of the IC is controlled by the NNS, any canister may also be controlled by its own DAO, called the **service nervous system (SNS)**. The DAO controlling a canister can control updates to the canister logic, as well as issuing privileged commands to be carried out by the canister.

Threshold ECDSA. ECDSA signatures [JMV01] are used in cryptocurrencies, such as Bitcoin and Ethereum, as well as in many other applications. While threshold signatures are already an essential ingredient in the IC, these are not threshold ECDSA signatures. This feature allows individual canisters to control an ECDSA signing key, which is securely distributed among all of the replicas on the subnet hosting the canister.

Bitcoin and Ethereum integration. Building on the new threshold ECDSA feature, this feature allows canisters to interact with the Bitcoin and Ethereum blockchains, including the ability to sign transactions.

HTTPs outcalls. This feature allows canisters to send HTTPs requests arbitrary web pages (external to the IC) and process the response after it has been agreed upon by consensus.

2 Architecture overview

As illustrated in Figure 1, the Internet Computer Protocol consists of four layers:

- peer-to-peer layer (see Section 4);
- consensus layer (see Section 5);

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- routing layer (see Section 6);
- execution layer (see Section 7).

Chain-key cryptography impacts several layers, and is discussed in detail in Sections 3 (threshold signatures) and 8 (chain-evolution technology).

2.1 Peer-to-peer layer

The peer-to-peer layer's task is to transport protocol messages between the replicas in a subnet. These protocol messages consist of

- messages used to implement consensus,
- input messages generated by an external user.

Basically, the service provided by the peer-to-peer is a "best effort" broadcast channel:

> *if an honest replica broadcasts a message, then that message will eventually be received by all honest replicas in the subnet.*

Design goals include the following:

- **Bounded resources.** All algorithms must work with bounded resources (memory, bandwidth, CPU).
- **Prioritization.** Different messages may be treated with different priorities, depending on certain attributes (e.g., type, size, round), and these priorities may change over time.
- **Efficiency.** High throughput is more important than low latency.
- **DOS/SPAM resilience.** Corrupt replicas should not prevent honest replicas from communicating with one another.

2.2 Consensus layer

The job of the consensus layer of the IC is to order inputs so that all replicas in a subnet will process such inputs in the same order. There are many protocols in the literature for this problem. The IC uses a new consensus protocol, which is described here at a high level.

Any secure consensus protocol should guarantee two properties, which (roughly stated) are:

- **safety**: all replicas in fact agree on the same ordering of inputs, and
- **liveness**: all replicas should make steady progress.

The IC consensus protocol is designed to be

- extremely simple, and
- robust: performance degrades gracefully when some replicas are malicious.

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As discussed above, we assume $f < n/3$ faulty (i.e., Byzantine) replicas. Also, liveness holds under a partial synchrony assumption, while safety is guaranteed, even in a completely asynchronous network.

Like a number of consensus protocols, the IC consensus protocol is based on a blockchain. As the protocol progresses, a tree of blocks is grown, starting from a special **genesis block** that is the root of the tree. Each non-genesis block in the tree contains (among other things) a **payload**, consisting of a sequence of inputs, and a hash of the block's parent in the tree. The honest replicas have a consistent view of this tree: while each replica may have a different, partial view of this tree, all the replicas have a view of the *same* tree. In addition, as the protocol progresses, there is always a path of **finalized** blocks in this tree. Again, the honest replicas have a consistent view of this path: while each replica may have a different, partial view of this path, all the replicas have a view of the *same* path. The inputs in the payloads of the blocks along this path are the ordered inputs that will be processed by the execution layer of the Internet Computer.

The protocol proceeds in **rounds**. In round h of the protocol, one or more blocks of **height** h are added to the tree. That is, the blocks added in round h are always at a distance of exactly h from the root. In each round, a pseudo-random process is used to assign each replica a unique **rank**, which is an integer in the range $0, \ldots, n-1$. This pseudo-random process is implemented using a **Random Beacon** (this makes use of threshold signatures, mentioned above in Section 1.6.1 and discussed in more detail in Section 3). The replica of lowest rank is the **leader** of that round. When the leader is honest and the network is synchronous, the leader will propose a block, which will be added to the tree; moreover, this will be the *only* block added to the tree in this round and it will extend the finalized path. If the leader is not honest or the network is not synchronous, some other replicas of higher rank may also propose blocks, and also have their blocks added to the tree. In any case, the logic of the protocol gives highest priority to the leader's proposed block and *some* block or blocks will be added to this tree in this round. Even if the protocol proceeds for a few rounds without extending the finalized path, the height of the tree will continue to grow with each round, so that when the finalized path is extended in round h, the finalized path will be of length h. A consequence of this, even if the *latency* occasionally increases because of faulty replicas or unexpectedly high network latency, the *throughput* of the protocol remains essentially constant.

The consensus protocol relies on digital signatures to authenticate messages sent between replicas. To implement the protocol, each replica is associated with a public verification key for a signature scheme. The association of replicas to public keys is obtained from the registry maintained by the NNS.

2.3 Message routing

As discussed in Section 1.7, basic computational unit in the IC is called a **canister**. The IC provides a run-time environment for executing programs in a canister, and to communicate with other canisters and external users (via message passing).

The consensus layer bundles inputs into **payloads**, which get placed into **blocks**, and as blocks are finalized, the corresponding payloads are delivered to the **message routing** layer, then processed by the **execution environment**, which updates the state of the

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canisters on the replicated state machine and generates outputs, and these outputs are processed by the **message routing** layer.

It is useful to distinguish between two types of inputs:

ingress messages: these are messages from external users;

cross-subnet messages: these are messages from canisters on other subnets.

We can also distinguish between two types of outputs:

ingress message *responses*: these are responses to ingress messages (which may be retrieved by external users);

cross-subnet messages: these are messages to canisters on other subnets.

Upon receiving a payload from consensus, the inputs in that payload are placed into various **input queues**. For each canister C running on a subnet, there are several input queues — there is one queue specifically for ingress messages to C, and each other canister C', with whom C communicates, gets its own queue. (In the case where C' is not located on the same subnet as C, these are cross-subnet messages.) In each round, the execution layer will consume some of the inputs in these queues, update the replicated state of the relevant canisters, and place outputs in various **output queues**. For each canister C running on a subnet, there are several output queues — each other canister C', with whom C communicates, gets its own queue. (In the case where C' is not located on the same subnet as C, these are cross-subnet messages.) The message routing layer will take the messages in these output queues and place them into **subnet-to-subnet streams** to be processed by a **crossnet transfer protocol**, whose job it is to actually transport these messages to other subnets.

In addition to these output queues, there is also an **ingress history** data structure. Once an ingress message has been processed by a canister, a **response** to that ingress message will be recorded in this data structure. At that point, the external user who provided the ingress message will be able to retrieve the corresponding response. (Note that *ingress history* does not maintain the full history of all ingress messages.)

Note that the replicated state comprises the state of the canisters, as well as "system state", including the above-mentioned queues and streams, as well as the *ingress history* data structure. Thus, both the message routing and execution layers are involved in updating and maintaining the replicated state of a subnet. It is essential that all of this state is updated in a completely *deterministic* fashion, so that all replicas maintain *exactly* the same state.

Also note that the consensus layer is decoupled from the message routing and execution layers, in the sense that any forks in the consensus blockchain are resolved before their payloads are passed to message routing, and in fact, consensus does not have to keep in lock step with message routing and consensus and is allowed to run a bit ahead.

2.3.1 Per-round certified state

In each round, *some* of the state of a subnet will be *certified*. The **per-round certified state** is certified using chain-key cryptography. Among other things, the certified state in a given round consists of

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- *cross-subnet messages* that were recently added to the subnet-to-subnet streams;
- other metadata, including the *ingress history* data structure.

The **per-round certified state** is certified using a threshold signature (see Section 1.6.1). Per-round certified state is used in several ways in the IC:

- *Output authentication.* Cross-subnet messages and responses to ingress messages are authenticated using per-round certified state.
- *Preventing and detecting non-determinism.* Consensus guarantees that each replica processes inputs in the same order. Since each replica processes these inputs deterministically, each replica should obtain the same state. However, the IC is designed with an extra layer of robustness to prevent and detect any (accidental) non-deterministic computation, should it arise. The per-round certified state is one of the mechanisms used to do this.
- *Coordination with consensus.* The per-round certified state is also used to coordinate the execution and consensus layers, in two different ways:
  - If consensus is running ahead of execution (whose progress is determined by the last round whose state is certified), consensus will be "throttled".
  - Inputs to consensus must pass certain validity checks, and these validity checks may depend on certified state, which all replicas must agree upon.

2.3.2 Query calls vs update calls

As we have described it so far, ingress messages must pass through consensus so that they are processed in the same order by all replicas on a subnet. However, an important optimization is available to those ingress messages whose processing does not modify the replicated state of a subnet. These are called **query calls** — as opposed to other ingress messages, which are called **update calls**. Query calls are allowed to perform computations which read and possibly update the state of a canister, but any updates to the state of a canister are never committed to the replicated state. As such, a query call may be processed directly by a single replica without passing through consensus, which greatly reduces the latency for obtaining a response from a query call.

In general, a response to a query call is not recorded in the *ingress history* data structure, and therefore cannot be authenticated using the per-round certified state mechanism as described above. However, the IC makes it possible for canisters to store data (while processing update calls) in special *certified variables*, which *can* be authenticated by this mechanism; as such, query calls that return as their value a certified variable can still be authenticated.

2.3.3 External user authentication

One of the main differences between an ingress message and a cross-subnet message is the mechanism used for authenticating these messages. While chain-key cryptography is used

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to authenticate cross-subnet messages, a different mechanism is used to authenticate ingress messages from external users.

There is no central registry for external users. Rather, an external user identifies himself to a canister using a **user identifier** (aka *principal*), which is a hash of a public signature-verification key. The user holds a corresponding secret signing key, which is used to sign ingress messages. Such a signature, as well as the corresponding public key, is sent along with the ingress message. The IC automatically authenticates the signature and passes the user identifier to the appropriate canister. The canister may then authorize the requested operation, based on the user identifier and other parameters to the operation specified in the ingress message.

First-time users generate a key pair and derive their user identifier from the public key during their first interaction with the IC. Returning users are authenticated using the secret key that is stored by the user agent. A user may associate several key pairs with a single user identity, using signature delegation. This is useful, as it allows a single user to access the IC from several devices using the same user identity.

2.4 Execution layer

The execution layer processes one input at a time. This input is taken from one of the input queues, and is directed to one canister. Based on this input and the state of the canister, the execution environment updates the state of the canister, and additionally may add messages to output queues and update the *ingress history* (possibly with a response to an earlier ingress message).

Each subnet has access to a **distributed pseudorandom generator (PRG)**. Pseudo-random bits are derived from a seed that itself is a threshold signature called the **Random Tape** (see Section 1.6.1 and more detail in Section 3). There is a different Random Tape for each round of the consensus protocol.

The basic properties of the random tape are:

1. Before a block at height h is finalized by any honest replica, the Random Tape at height $h + 1$ is guaranteed to be unpredictable.

2. By the time a block at height $h + 1$ is finalized by any honest replica, that replica will typically have all the shares it needs to construct the Random Tape at height $h + 1$.

To obtain pseudorandom bits, a subnet must make a request for these bits via a "system call" from the execution layer in some round, say h. The system will then respond to that request later, using the Random Tape at height $h+1$. By property (1) above, it is guaranteed that the requested pseudorandom bits are unpredictable at the time the request is made. Consensus will actually deliver to message routing both the Random Tape and payload at $h + 1$ at the same time; by property (2) above, this will typically not incur any additional delay.

2.5 Putting it all together

We trace through the typical flow to process a user request on the IC.

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Query call

1. A user's query call M to a canister C is sent by the user's client to a boundary node (see Section 1.9), and the boundary node sends M to a replica on the subnet that hosts canister C. After receiving M, this replica will compute the response and send it back to the user via the boundary node.

Update call

1. A user's request M to a canister C is sent by the user's client to a boundary node (see Section 1.9), and the boundary node sends M to a replica on the subnet that hosts canister C.

2. After receiving M, this replica will broadcast M to all other replicas on the subnet, using the peer-to-peer layer (see Section 2.1).

3. Having received M, the leader for the next round of consensus (see Section 2.2) will bundle M with other inputs to form the payload for a block B that the leader proposes.

4. Some time later, block B is finalized and the payload is sent to the message routing layer (see Section 2.3) for processing. Note that the peer-to-peer layer is also used by consensus to finalize this block.

5. The message routing layer will place M in the input queue of the canister C.

6. Some time later, the execution layer (see Section 2.4) will process M, updating the internal state of the canister C.

   In some situations, the canister C will be able to immediately compute a response R to the request M. In this case, R is placed in the ingress history data structure.

   In other situations, processing the request M may require making a request to another canister. In this example, let us suppose that to process this particular request M, the canister C must make a request M' to another canister C' that resides on another subnet. This second request M' will be placed in the output queue of C, and then the following steps are performed.

7. Some time later, message routing will move M' into an appropriate cross-subnet stream, and this will eventually be transported to the subnet hosting C'.

8. On the second subnet, the request M' will be obtained from the first subnet, and eventually pass through consensus and message routing on the second subnet and then be processed by execution. The execution layer will update the internal state of canister C' and generate a response R' to the request M'. The response R' will go in the output queue of canister C', and eventually be placed in a cross-subnet stream and transported back to the first subnet.

9. Back on the first subnet, the response R' will be obtained from the second subnet, and eventually pass through consensus and message routing on the first subnet and then be processed by execution. The execution layer will update the internal state

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of canister C and generate a response R to the original request message M. This response will be recorded in the ingress history data structure.

Regardless of which execution path is taken, the response R to request M will eventually be recorded in the ingress history data structure on the subnet that hosts canister C. To obtain this response, the user's client must perform a kind of "query call" (see Section 2.3.2). As discussed in Section 2.3.1, this response will be authenticated via chain-key cryptography (specifically, using a threshold signature). The authentication logic itself (i.e., threshold signature verification) will be performed by the client using the service worker originally obtained by the client from the boundary node.

3 Chain-key crytography I: threshold signatures

A critical component of the IC's chain-key cryptography is a threshold signature scheme [Des87]. The IC uses threshold signatures for a number of purposes. Let n be the number of replicas in a subnet and let f be a bound on the number of corrupt replicas.

- The Consensus Layer makes use of an $(f+1)$-out-of-n threshold signature to realize a *random beacon* (see Section 5.5).
- The Execution Layer makes use of an $(f+1)$-out-of-n threshold signature to realize a *random tape*, which is used to provide unpredictable pseudorandom numbers to canisters (see Section 7.1).
- The Execution Layer makes use of an $(n-f)$-out-of-n threshold signature to *certify the replicated state*. This is used both to authenticate the outputs of a subnet (see Section 6.1) and to implement the *fast-forwarding* feature of the IC's *chain-evolution technology* (see Section 8.2).

For the first two applications (the random beacon and random tape), it is essential that the threshold signatures are *unique*, i.e., for a given public key and message, there is only one valid signature. This is required as we use the signature as a seed to a pseudorandom generator, and all replicas who compute such a threshold signature must agree on the same seed.

3.1 Threshold BLS signatures

We implement threshold signatures based on the BLS signature scheme [BLS01], which is trivial to adapt to the threshold setting.

The ordinary (i.e., non-threshold) BLS signature scheme makes use of two groups, $\mathbb{G}$ and $\mathbb{G}'$, both of prime order q. We assume that $\mathbb{G}$ is generated by $g \in \mathbb{G}$ and $\mathbb{G}'$ is generated by $g' \in \mathbb{G}'$. We also assume a hash function $H_{\mathbb{G}'}$ that maps its inputs to $\mathbb{G}'$ (and which is modeled as a random oracle). The secret signing key is an element $x \in \mathbb{Z}_q$ and the public verification key is $V := g^x \in \mathbb{G}$.

In the non-threshold setting, to sign a message m, the signer computes $h' \leftarrow H_{\mathbb{G}'}(m) \in \mathbb{G}'$ and then computes the signature $\sigma := (h')^x \in \mathbb{G}'$. To verify that such a signature is valid, one must test if $\log_{h'} \sigma = \log_g V$. To be able to perform this test efficiently, the BLS scheme

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uses the notion of a **pairing** on the groups $\mathbb{G}$ and $\mathbb{G}'$, which is an algebraic operation that is available when $\mathbb{G}$ and $\mathbb{G}'$ are **elliptic curves** of a special type. We shall not be able to go into the details of pairings and elliptic curves here. See [BLS01] for more details. BLS signatures have the nice property (mentioned above) that signatures are unique.

In the t-out-of-n threshold setting, we have n replicas, any t of which may be used to generate a signature on a message. In somewhat more detail, each replica P_j holds a share $x_j \in \mathbb{Z}_q$ of the secret signing key $x \in \mathbb{Z}_q$, which is privately held by P_j, while the group element $V_j := g^{x_j}$ is publicly available. The shares $(x_1, \ldots, x_n)$ are a t-out-of-n secret-sharing of x (see Section 3.4).

Given a message m, replica P_j can generate a **signature share**

$$\sigma_j := (h')^{x_j} \in \mathbb{G}',$$

where $h' := H_{\mathbb{G}'}(m)$ as before. To verify that such a signature share is valid, one must test if $\log_{h'} \sigma_j = \log_g V_j$. Computing the discrete logarithms is intractable, but this can be checked using a pairing — in fact, this is exactly the same as the validity test for an ordinary BLS signature with public key V_j.

This scheme satisfies the following **reconstruction property**:

> *Given any collection of t valid signature shares σ_j on a message m (contributed by distinct replicas), we can efficiently compute a valid BLS signature σ on m under the public verification key.*
>
> *In fact, σ can be computed as*
>
> $$\sigma \leftarrow \prod_j \sigma_j^{\lambda_j}, \tag{1}$$
>
> *where the λ_j's can be efficiently computed just from the indices of the t contributing replicas.*

Under reasonable intractability assumptions for $\mathbb{G}$, and modeling $H_{\mathbb{G}'}$ as a random oracle, this scheme satisfies the following **security property**:

> *Assume that at most f replicas may be corrupted by an adversary. Then it is infeasible for the adversary to compute a valid signature on a message unless it obtains signature shares on that message from at least $t - f$ honest replicas.*

3.2 Distributed key distribution

To implement threshold BLS, we need a way to distribute the shares of the secret signing key to the replicas. One way to do this would be to have a **trusted party** compute all of these shares directly and distribute them to all the replicas. Unfortunately, this would create a single point of failure. Instead, we use a **distributed key generation (DKG) protocol**, which allows the replicas to essentially carry out the logic of such a trusted party using a secure distributed protocol.

We sketch the high level ideas of the protocol currently implemented. We refer the reader to [Gro21] for more details. The DKG protocol used is essentially non-interactive. It uses two essential ingredients:

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- a **publicly verifiable secret sharing (PVSS)** scheme, and
- a **consensus** protocol.

Although any consensus protocol could be used, not surprisingly, the one we use is that in Section 5 (see also Section 8).

3.3 Assumptions

The basic assumptions made are the same as outlined in Section 1:

- asynchronous communication, and
- $f < n/3$.

We only indirectly make use of a *partial* synchrony assumption (as in Section 5.1) to ensure that the consensus protocol attains liveness.

We also assume that for a t-out-of-n threshold signature scheme, we have

$$f < t \leq n - f,$$

which (among other things) ensures that (1) the corrupt replicas cannot sign all by themselves, and (2) the honest replicas can sign all by themselves.

We also assume that every replica is associated with some public keys, where each replica also holds the corresponding private key. One public key is the signing key (the same one as in Section 5.4). Another public key is a public encryption key for a specific public-key encryption scheme needed to implement the PVSS scheme (details follow).

3.4 PVSS scheme

Let $\mathbb{G}$ be the group of prime order q generated by $g \in \mathbb{G}$ introduced above. Let $s \in \mathbb{Z}_q$ be a secret. Recall that a t-out-of-n Shamir secret-sharing of s is a vector $(s_1, \ldots, s_n) \in \mathbb{Z}_q^n$, where

$$s_j \coloneqq a(j) \quad (j = 1, \ldots, n).$$

and

$$a(x) \coloneqq a_0 + a_1 x + \cdots + a_{t-1} x^{t-1} \in \mathbb{Z}_q[x]$$

is a polynomial of degree less than t with $a_0 \coloneqq s$. The key properties of such a secret sharing are

- from any collection of t of the s_j's, we can efficiently compute (via polynomial interpolation) the secret $s = a_0 = a(0)$, and
- if $a_1, \ldots, a_{t-1}$ are chosen uniformly and independently over $\mathbb{Z}_q$, then any collection of fewer than t of the s_j's reveals no information about the secret s.

At a high level, a PVSS scheme allows one replica, P_i, called the **dealer**, to take such a sharing, and compute an object called a **dealing**, which contains

- a vector of group elements $(A_0, \ldots, A_{t-1})$, where $A_k \coloneqq g^{a_k}$ for $k = 0, \ldots, t-1$,

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- a vector of ciphertexts $(c_1, \ldots, c_n)$, where c_j is the encryption of s_j under P_j's public encryption key,
- a non-interactive zero-knowledge proof π that each c_j does indeed encrypt such a share — more precisely, that each c_j decrypts the value s_j satisfying

$$g^{s_j} = \prod_{k=0}^{t-1} A_k^{j^k} = g^{a(j)}. \tag{2}$$

We note that to establish the overall security of our DKG protocol, the PVSS scheme must provide an appropriate level of chosen ciphertext security. Specifically, the dealer must embed its identity as *associated data* in the dealing, and the encrypted shares must remain hidden, even under a chosen ciphertext attack wherein an adversary is allowed to decrypt arbitrary dealings which are decrypted under associated data that is distinct from the associated data used to create the dealing.

It is easy to realize a PVSS scheme, if one is not too concerned about efficiency. The idea is to use an ElGamal-like encryption scheme to encrypt each s_j bit by bit, and then use a standard non-interactive zero-knowledge proof for the relation (2), which would be based on a standard application of the Fiat-Shamir transform (see [FS86]) to an appropriate Sigma protocol (see [CDS94]). While this yields a polynomial-time scheme, it is not that practical. However, there are many possible ways to optimize this type of scheme. See [Gro21] for the details on the highly optimized PVSS scheme used in the IC.

3.5 The basic DKG protocol

Using the PVSS scheme and a consensus protocol, the basic DKG protocol is very simple.

1. Each replica broadcasts a **signed dealing** of a random secret to all other replicas.

   Such a signed dealing includes a dealing, along with the identity of the dealer and a signature on the dealing under the dealer's public signing key.

   Such a signed dealing is called **valid** if it has the right syntactic form, and the signature and non-interactive zero knowledge proof are valid.

2. Using consensus the replicas agree on a set S of $f + 1$ valid signed dealings (from distinct dealers).

3. Suppose that the ith dealing in the set S contains the vector of group elements $(A_{i,0}, \ldots, A_{i,t-1})$ and the vector of ciphertexts $(c_{i,1}, \ldots, c_{i,n})$.

   Then the public verification key for the threshold signature scheme is

   $$V := \prod_i A_{i,0}.$$

   Note that the secret signing key is implicitly defined as

   $$x := \log_g V.$$

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P_j's share of the secret signing key x is

$$x_j \coloneqq \sum_i s_{i,j},$$

where $s_{i,j}$ is the decryption of $c_{i,j}$ under P_j's secret decryption key.

The public verification key for replica P_j is

$$V_j \coloneqq \prod_i \prod_{k=0}^{t-1} A_{i,k}^{j^k} = g^{x_j}.$$

Note that the shares x_j comprise a t-out-of-n Shamir secret-sharing of x. As such, the λ_j values appearing in (1) are just Lagrange interpolation coefficients. This establishes the *reconstruction property* stated in Section 3.1. As for the security property stated in Section 3.1, this can be proved to hold modeling $H_{\mathbb{G}'}$ as a random oracle, and assuming that the PVSS scheme is secure, and that the groups $\mathbb{G}$ and $\mathbb{G}'$ (with a pairing) satisfy a certain type of **one-more Diffie-Hellman** hardness assumption, which can be stated as saying that no efficient adversary can win the following game with non-negligible probability:

> *The challenger chooses $\mu_1, \ldots, \mu_k \in \mathbb{Z}_q$ and $\nu_1, \ldots, \nu_\ell \in \mathbb{Z}_q$ at random, and gives $\{g^{\mu_i}\}_{i=1}^k$ and $\{(g')^{\nu_j}\}_{j=1}^\ell$ to the adversary.*
>
> *The adversary makes a sequence of queries to the challenger, each of which is a vector of the form $\{\kappa_{i,j}\}_{i,j}$, to which the challenger responds with*
>
> $$\prod_{i,j} \left((g')^{\mu_i \nu_j}\right)^{\kappa_{i,j}}.$$
>
> *To end the game, the adversary outputs a vector $\{\lambda_{i,j}\}_{i,j}$ and a group element $h' \in \mathbb{G}'$, and wins the game if*
>
> $$h' = \prod_{i,j} \left((g')^{\mu_i \nu_j}\right)^{\lambda_{i,j}}$$
>
> *and the output vector $\{\lambda_{i,j}\}_{i,j}$ is not a linear combination of the query vectors.*

While this type of one-more Diffie-Hellman assumption is needed in the case where $t > f + 1$, one can get by with a weaker assumption when $t = f + 1$ (the so-called co-CDH assumption, on which the security of the ordinary BLS scheme is based).

3.6 A resharing protocol

The basic DKG protocol can be easily modified so that instead of creating a sharing of a fresh random secret x, it instead creates a fresh, random sharing of a previously shared secret.

- Step 1 of the basic protocol is modified so that each replica broadcasts a signed dealing of its existing share.

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- Step 2 is modified so that a set of t valid signed dealings is agreed upon. Also, each dealing is verified to ensure that it is indeed a dealing of the appropriate existing share (this means that the value of $A_{i,0}$ in the ith dealing should be equal to the old value of V_i).
- In Step 3, the computation of the new x_j (and V_j) values weight the sum (and product) on i Lagrange interpolation coefficients.

4 Peer-to-peer layer

The peer-to-peer layer's task is to transport protocol messages between the replicas in a subnet. These protocol messages consist of

- messages used to implement consensus, e.g., block proposals, notarizations, etc. (see Section 5);
- ingress messages (see Section 6).

Basically, the service provided by the peer-to-peer is a "best effort" broadcast channel:

> *if an honest replica broadcasts a message, then that message will eventually be received by all honest replicas in the subnet.*

Design goals include the following:

- **Bounded resources.** All algorithms must work with bounded resources (memory, bandwidth, CPU).
- **Prioritization.** Different messages may be treated with different priorities, depending on certain attributes (e.g., type, size, round), and these priorities may change over time.
- **Efficiency.** High throughput is more important than low latency.
- **DOS/SPAM resilience.** Corrupt replicas should not prevent honest replicas from communicating with one another.

Observe that in the consensus protocol, some messages, notably block proposals (which can be quite large), will be rebroadcast by all replicas. This is necessary to ensure correct behavior of that protocol. However, if implemented naively, this would be a huge waste of resources. To avoid having all replicas broadcasting the same message, the peer-to-peer layer makes use of an **advertise-request-deliver** mechanism. Instead of broadcasting a (large) message directly, it will instead broadcast a (small) **advertisement** for the message: if a replica receives such an advertisement for a message, which it has not already received, and deems the message to be important, it will **request** that the message is **delivered**. This strategy decreases bandwidth utilization at the cost of higher latency. For small messages, this trade-off is not worthwhile, and it makes more sense to just send the message directly, rather than an advertisement.

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For relatively small subnets, a replica that wishes to broadcast a message will send an advertisement to all replicas in the subnet, each of which may then request that the message is delivered. For larger subnets, this advertise-request-deliver mechanism may operate over an **overlay network**. An overlay network is a connected, undirected graph whose vertices comprise the replicas in a subnet. Two replicas are **peers** if there is an edge connecting them in this graph, and a replica only communicates with its peers. So when a replica wishes to broadcast a message, it sends an advertisement for that message to its peers. Those peers may request that the message be delivered, and upon receiving the message, if certain conditions are met, those peers will advertise the message to their peers. This is essentially a **gossip network**. This strategy again decreases bandwidth utilization at the cost of even higher latency.

5 Consensus Layer

The job of the consensus layer of the IC is to order inputs so that all replicas in a subnet will process such inputs in the same order. There are many protocols in the literature for this problem. The IC uses a new consensus protocol, which is described here at a high level. For more details, see the paper [CDH+21] (in particular, Protocol ICC1 in that paper).

Any secure consensus protocol should guarantee two properties, which (roughly stated) are:

- **safety**: all replicas in fact agree on the same ordering of inputs, and
- **liveness**: all replicas should make steady progress.

The paper [CDH+21] proves that the IC consensus protocol satisfies both of these properties.

The IC consensus protocol is designed to be

- extremely simple, and
- robust: performance degrades gracefully when some replicas are malicious.

5.1 Assumptions

As discussed in the introduction, we assume

- a subnet of n replicas, and
- at most $f < n/3$ of the replicas are faulty.

Faulty replicas may exhibit arbitrary, malicious (i.e., Byzantine) behavior.

We assume that communication is **asynchronous**, with no *a priori* bound on the delay of messages sent between replicas. In fact, the scheduling of message delivery may be completely under adversarial control. The IC consensus protocol guarantees safety under this very weak communication assumption. However, to guarantee liveness, we need to assume a form of **partial synchrony**, which (roughly stated) says that the network will be periodically synchronous for short intervals of time. In such intervals of synchrony, all

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undelivered messages will be delivered in less than time δ, for some fixed bound δ. The bound δ does not have to be known in advance (the protocol is initialized with a reasonable bound, but will dynamically adapt and increase this bound if it is too small). Regardless of whether we are assuming an asynchronous or a partially synchronous network, we assume that every message sent from one honest replica to another will *eventually* be delivered.

5.2 Protocol overview

Like a number of consensus protocols, the IC consensus protocol is based on a blockchain. As the protocol progresses, a tree of blocks is grown, starting from a special **genesis block** that is the root of the tree. Each non-genesis block in the tree contains (among other things) a **payload**, consisting of a sequence of inputs, and a hash of the block's parent in the tree. The honest replicas have a consistent view of this tree: while each replica may have a different, partial view of this tree, all the replicas have a view of the *same* tree. In addition, as the protocol progresses, there is always a path of **finalized** blocks in this tree. Again, the honest replicas have a consistent view of this path: while each replica may have a different, partial view of this path, all the replicas have a view of the *same* path. The inputs in the payloads of the blocks along this path are the ordered inputs that will be processed by the execution layer of the Internet Computer (see Section 7).

The protocol proceeds in **rounds**. In round h of the protocol, one or more blocks of **height** h are added to the tree. That is, the blocks added in round h are always at a distance of exactly h from the root. In each round, a pseudo-random process is used to assign each replica a unique **rank**, which is an integer in the range $0, \ldots, n-1$. This pseudo-random process is implemented using a **random beacon** (see Section 5.5 below). The replica of lowest rank is the **leader** of that round. When the leader is honest and the network is synchronous, the leader will propose a block, which will be added to the tree; moreover, this will be the *only* block added to the tree in this round and it will extend the finalized path. If the leader is not honest or the network is not synchronous, some other replicas of higher rank may also propose blocks, and also have their blocks added to the tree. In any case, the logic of the protocol gives highest priority to the leader's proposed block and *some* block or blocks will be added to this tree in this round. Even if the protocol proceeds for a few rounds without extending the finalized path, the height of the tree will continue to grow with each round, so that when the finalized path is extended in round h, the finalized path will be of length h. A consequence of this, even if the *latency* occasionally increases because of faulty replicas or unexpectedly high network latency, the *throughput* of the protocol remains essentially constant.

5.3 Additional properties

An additional property enjoyed by the IC consensus protocol (just like PBFT [CL99] and HotStuff [YMR$^+$18], and unlike others, such as Tendermint [BKM18]) is *optimistic responsiveness* [PS18], which means that when the leader is honest, the protocol may proceed at the pace of the actual network delay, rather than some upper bound on the network delay.

We note that the simple design of the IC consensus protocol also ensures that its performance degrades quite gracefully when and if Byzantine failures actually do occur. As pointed out in [CWA$^+$09], much of the recent work on consensus has focused so much

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on improving the performance in the "optimistic case" where there are no failures, that the resulting protocols are dangerously fragile, and may become practically unusable when failures do occur. For example, [CWA+09] show that the throughput of existing implementations of PBFT drops to zero under certain types of (quite simple) Byzantine behavior. The paper [CWA+09] advocates for *robust* consensus, in which *peak* performance under optimal conditions is partially sacrificed in order to ensure *reasonable* performance when some parties actually are corrupt (but still assuming the network is synchronous). The IC consensus protocols is indeed robust in the sense of [CWA+09]: in any round where the leader is corrupt (which itself happens with probability less than 1/3), the protocol will effectively allow another party to take over as leader for that round, with very little fuss, to move the protocol forward to the next round in a timely fashion.

5.4 Public keys

To implement the protocol, each replica is associated with a public key for the BLS signature scheme [BLS01], and each replica also holds the corresponding secret signing key. The association of replicas to public keys is obtained from the registry maintained by the NNS (see Section 1.5). These BLS signatures will be used to authenticate messages sent by replicas.

The protocol also uses the **signature aggregation** feature of BLS signatures [BGLS03], which allows many signatures on the same message to be aggregated into a compact multi-signature. The protocol will use these multi-signatures for **notarizations** (see Section 5.7) and **finalizations** (see Section 5.8), which are aggregations of $n - f$ signatures on messages of a certain form.

5.5 Random Beacon

In addition to BLS signatures and multi-signatures as discussed above, the protocol makes use of a BLS threshold signature scheme to implement the above-mentioned random beacon. The random beacon for height h is a $(f + 1)$-threshold signature on a message unique to height h. In each round of the protocol, each replica broadcasts its share of the beacon for the next round, so that when the next round begins, all replicas should have enough shares to reconstruct the beacon for that round. As discussed above, the random beacon at height h is used to assign a pseudo-random rank to each replica that will be used in round h of the protocol. Because of the security properties of the threshold signature, an adversary will not be able to predict the ranking of the replicas more than one round in advance, and these rankings will effectively be as good as random. See Section 3 for more on BLS threshold signatures.

5.6 Block making

Each replica may at different points in time play the role of a **block maker**. As a block maker in round h, the replica proposes a block B of height h that is to be a child of some block B' of height $h - 1$ in the tree of blocks. To do this, the block maker first gathers together a **payload** consisting of all inputs it knows about (but not including those already

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included in payloads in blocks in the path through the tree ending at B'). The block B consists of

- the payload,
- the hash of B',
- the rank of the block maker,
- the height h of the block.

After forming the block B, the block maker forms a **block proposal**, consisting of

- the block B,
- the block maker's identity, and
- the block maker's signature on B.

A block maker will broadcast its block proposal to all other replicas.

5.7 Notarization

A block is effectively added to the tree of blocks when it becomes **notarized**. For a block to become notarized, $n - f$ distinct replicas must **support** its notarization.

Given a proposed block B at height h, a replica will determine if the proposal is **valid**, which means that B has the syntactic form described above. In particular, B should contain the hash of a block B' of height h' that is already in the tree of blocks (i.e., already notarized). In addition, the payload of B must satisfy certain conditions (in particular, all of the inputs in the payload must satisfy various constraints, but these constraints are generally independent of the consensus protocol). Also, the rank of the block maker (as recorded in the block B) must match the rank assigned in round h by the random beacon to the replica that proposed the block (as recorded in the block proposal) .

If the block is valid and certain other constraints hold, the replica will **support** the notarization of the block by broadcasting a **notarization share** for B, consisting of

- the hash of B,
- the height h of B,
- the identity of the supporting replica, and
- the supporting replica's signature on a message comprising the hash of B and the height h.

Any set of $n - f$ notarization shares on B may be aggregated together to form a **notarization** for B, consisting of

- the hash of B,
- the height h of B,

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- the set of identities of the $n - f$ supporting replicas,
- an aggregation of the $n - f$ signatures on the message comprising the hash of B and the height h.

As soon as a replica obtains a notarized block of height h, it will finish round h, and will subsequently not support the notarization of any other blocks at height h. At this point in time, such a replica will also *relay this notarization to all other replicas*. Note that this replica may have obtained the notarization either by (1) receiving it from another replica, or (2) aggregating $n - f$ notarization shares that it has received.

The **growth invariant** states that each honest replica will eventually complete each round and start the next, so that the tree of notarized blocks continues to grow (and this holds only assuming asynchronous eventual delivery, and not partial synchrony). We prove the growth invariant below (see Section 5.11.4).

5.8 Finalization

There may be more than one notarized block at a given height h. However, if a block is **finalized**, then we can be sure that there is no other notarized block at height h. Let us call this the **safety invariant**.

For a block to become finalized, $n - f$ distinct replicas must **support** its finalization. Recall that round h ends for a replica when it obtains a notarized block B of height h. At that point in time, such a replica will check if it supported the notarization of any block at height h *other* than block B (it may or may not have supported the notarization of B itself). If not, the replica will **support** the finalization of B by broadcasting a **finalization share** for B. A finalization share has exactly the same format as a notarization share (but is tagged in such a way notarization shares and finalization shares cannot be confused with one another). Any set of $n - f$ finalization shares on B may be aggregated together to form a **finalization** for B, which has exactly the same format as a notarization (but again, is appropriately tagged). Any replica that obtains a finalized block will broadcast the finalization to all other replicas.

We prove the safety invariant below (see Section 5.11.5). One consequence of the safety invariant is the following. Suppose two blocks B and B' are finalized, where B has height h, B' has height $h' \leq h$. Then the safety invariant implies that the path in the tree of notarized blocks ending at B' is a prefix of the path ending at B (if not, then there would be two notarized blocks at height h', contradicting the finalization invariant). Thus, whenever a replica sees a finalized block B, it may view all ancestors of B as being **implicitly finalized**, and because of the safety invariant, the safety property is guaranteed to hold for these (explicitly and implicitly) finalized blocks — that is, all replicas agree on the ordering of these finalized blocks.

5.9 Delay functions

The protocol makes use of two **delay functions**, Δ_{m} and Δ_{n}, which control the timing of block making and notarization activity. Both of these functions map the rank r of the proposing replica to a nonnegative delay amount, and it is assumed that each function

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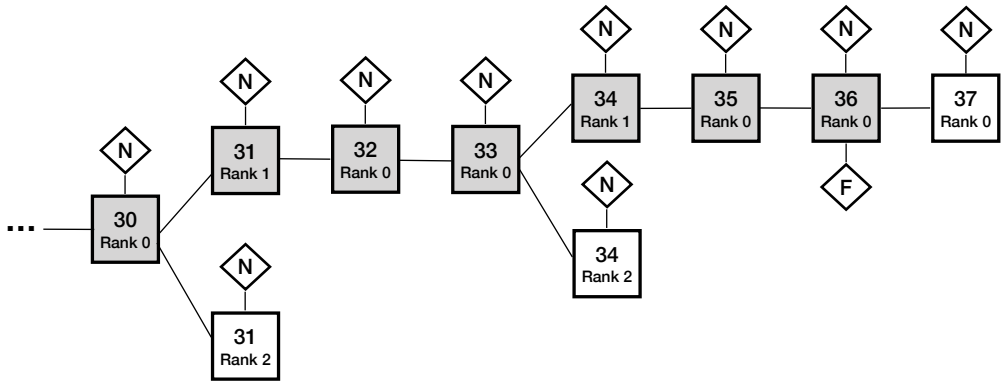


Figure 2: An example tree of blocks

is monotonely increasing in r, and that $\Delta_{\mathrm{m}}(r) \leq \Delta_{\mathrm{n}}(r)$ for all $r = 0, \ldots, n-1$. The recommended definition of these functions is $\Delta_{\mathrm{m}}(r) = 2\delta r$ and $\Delta_{\mathrm{n}}(r) = 2\delta r + \epsilon$, where δ is an upper bound on the time to deliver messages from one honest replica to another, and $\epsilon \geq 0$ is a "governor" to keep the protocol from running too fast. With these definitions, liveness will be ensured in those rounds in which (1) the leader is honest, and (2) messages really are delivered between honest replicas within time δ. Indeed, if (1) and (2) both hold in a given round, then the block proposed by the leader in that round will be finalized. Let us call this the **liveness invariant**. We prove this below (see Section 5.11.6).

5.10 An example

Figure 2 illustrates a block tree. Each block is labeled with its height (30, 31, 32, ...) and the rank of its block maker. The figure also shows that each block in the tree is notarized, as indicated by the $\langle \mathrm{N} \rangle$ symbol. This means that for each notarized block in the tree, at least $n - f$ distinct replicas supported its notarization. As one can see, there can be more than one notarized block in the tree at a given height. For example, at height 31, we see there are two notarized blocks, proposed by block makers of rank 1 and 2. The same thing happens at height 34. We can also see that the block at height 36 is also explicitly finalized, as indicated by the $\langle \mathrm{F} \rangle$ symbol. This means that $n - f$ distinct replicas supported this block's finalization, which means that these replicas (or at least, the honest replicas among these) did not support the notarization of any other block. All of the ancestors of this block, which are shaded gray, are considered implicitly finalized.

5.11 Putting it all together

We now describe in more detail how the protocol works; specifically, we describe more precisely when a replica will propose a block and when a replica will support the notarization of a block. A given replica P will record the time at which it enters a given round h, which happens when it has obtained (1) some notarization for a block of height $h-1$, and (2) the

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random beacon for round h. Since the random beacon for round h has been determined, P can determine its own rank r_P, as well as the rank r_Q of each other replica Q for round h.

5.11.1 Random beacon details

As soon as a replica has received the random beacon for round h, or enough shares to contruct the random beacon for round h, it will *relay the random beacom for round h to all other replicas*. As soon as a replica enters round h, it will generate and broadcast its share of the random beacon at round $h + 1$.

5.11.2 Block making details

Replica P will only propose its own block B_P provided (1) at least $\Delta_{\text{m}}(r_P)$ time units have passed since the beginning of the round, and (2) there is no valid lower ranked block currently seen by P.

Note that since P is guaranteed to have a notarized block of height $h - 1$ when it enters round h, it can make its proposed block a child of this notarized block (or any other notarized block of height $h - 1$ that it may have). Also note that when P broadcasts its proposal for B_P, it must also ensure that it also has *relayed the notarization of B_P's parent to all replicas*.

Suppose a replica Q sees a valid block proposal from a replica P of rank $r_P < r_Q$ such that (1) at least $\Delta_{\text{m}}(r_P)$ time units have passed since the beginning of the round, and (2) there is no block of rank less than r_P currently seen by Q. Then at this point in time, if it has not already done so, Q will *relay this block proposal (along with the notarization of the proposed block's parent) to all other replicas*.

5.11.3 Notarization details

Replica P will support the notarization of a valid block B_Q proposed by a replica Q of rank r_Q provided (1) at least $\Delta_{\text{n}}(r_Q)$ time units have passed since the beginning of the round, and (2) there is no block of rank less than r_Q currently seen by P.

5.11.4 Proof of growth invariant

The growth invariant states that each honest replica will eventually complete each round and start the next. Assume that all honest replicas have started round h. Let r^* be the rank of the lowest ranked honest replica P^* in round h. Eventually, P^* will either (1) propose its own block, or (2) relay a valid block proposed by a lower ranked replica. In either case, some block must eventually be supported by all honest replicas, which means that some block will become notarized and all honest replicas will finish round h. All honest replicas will also receive the shares needed to construct the random beacon for round $h + 1$, and so will start round $h + 1$.

5.11.5 Proof of safety invariant

The **safety invariant** states that if a block is finalized in a given round, then no other block may be notarized in that round. Here is a proof of the safety invariant:

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1. Suppose that the number of corrupt replicas is exactly $f^* \leq f < n/3$.

2. If a block B is finalized, then its finalization must have been supported by a set S of at least $n - f - f^*$ honest replicas (by the security property for aggregate signatures).

3. Suppose (by way of contradiction) that another block $B' \neq B$ were notarized. Then its notarization must have been supported by a set S' of at least $n - f - f^*$ honest replicas (again, by the security property for aggregate signatures).

4. The sets S and S' are disjoint (by the finalization logic).

5. Therefore, $n - f^* \geq |S \cup S'| = |S| + |S'| \geq 2(n - f - f^*)$, which implies $n \leq 3f$, a contradiction.

5.11.6 Proof of liveness invariant

We say that the network is **δ-synchronous at time** t if all messages that have been sent by honest replicas at or before time t arrive at their destinations before time $t + \delta$.

The **liveness invariant** may be stated as follows. Suppose that $\Delta_{\mathrm{n}}(1) \geq \Delta_{\mathrm{m}}(0) + 2\delta$. Also suppose that in a given round h, we have

- the leader P in round h is honest,
- the first honest replica Q to enter round h does so at time t, and
- the network is δ-synchronous at times t and $t + \delta + \Delta_{\mathrm{m}}(0)$.

Then the block proposed by P in round h will be finalized.

Here is a proof of the liveness invariant:

1. Under partial synchrony at time t, all honest replicas will enter round h before time $t + \delta$ (the notarization that ended round $h - 1$ for Q as well as the random beacon for round h random will arrive at all honest replicas before this time).

2. The leader P in round h will propose a block B before time $t + \delta + \Delta_{\mathrm{m}}(0)$, and again by partial synchrony, this block proposal will be delivered to all other replicas before time $t + 2\delta + \Delta_{\mathrm{m}}(0)$.

3. Since $\Delta_{\mathrm{n}}(1) \geq \Delta_{\mathrm{m}}(0) + 2\delta$, the protocol logic guarantees that each honest replica supports the notarization of block B and no other block, and thus B will become notarized and finalized.

5.12 Other issues

5.12.1 Growth latency

Under a partial synchrony assumption, we can also formulate and prove a quantitative version of the growth invariant. For simplicity, assume that the delay functions are defined as recommended above: $\Delta_{\mathrm{m}}(r) = 2\delta r$ and $\Delta_{\mathrm{n}}(r) = 2\delta r + \epsilon$, and further assume that $\epsilon \leq \delta$. Suppose that at time t, the highest numbered round entered by any honest replica is h. Let

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r^* be the rank of the lowest ranked honest replica P^* in round h. Finally, suppose that the network is δ-synchronous at all times in the interval $[t, t + (3r^* + 2)\delta]$. Then all honest replicas will start round $h + 1$ before time $t + 3(r^* + 1)\delta$.

5.12.2 Locally adjusted delay functions

When a replica does not see any finalized blocks for several rounds, it will start increasing its own delay function Δ_{n} for notarization. Replicas need not agree on these locally adjusted notarization delay functions.

Also, while replicas do not explicitly adjust the delay function Δ_{p}, we can mathematically model local clock drift by locally adjusting both delay functions.

Thus, there are many delay functions, parameterized by replica and round. The critical condition $\Delta_{\mathrm{n}}(1) \geq \Delta_{\mathrm{m}}(0) + 2\delta$ needed for liveness then becomes $\max \Delta_{\mathrm{n}}(1) \geq \min \Delta_{\mathrm{m}}(0) + 2\delta$, where the max and min are taken over all the honest replicas in a given round. Thus, if finalization fails for enough rounds, all honest replicas will eventually increase their notarization delay until this holds and finalization will then resume. If some honest replicas increase their notarization latency function more than other replicas, there is no penalty in terms of liveness (but there may be in terms of growth latency).

5.12.3 Fairness

Another property that is important in consensus protocols is **fairness**. Rather than give a general definition, we simply observe that the liveness invariant also implies a useful fairness property. Recall that the liveness invariant basically says that in any round where the leader is honest and the network is synchronous, then the block proposed by the leader will be finalized. In those rounds where this happens, the fact that the leader is honest ensures that it will include in the payload of its block all of the inputs it knows about (modulo limits on the payload size). So, very roughly speaking, any input that is disseminated to enough replicas will be included in a finalized block in a reasonable amount of time with high probability.

6 Message Routing Layer

As discussed in Section 1.7, basic computational unit in the IC is called a **canister**, which is roughly the same as the notion of a *process*, in that it comprises both a *program* and its *state*. The IC provides a run-time environment for executing programs in a canister, and to communicate with other canisters and external users (via message passing).

The consensus layer (see Section 5) bundles inputs into **payloads**, which get placed into **blocks**, and as blocks are finalized, the corresponding payloads are delivered to the **message routing** layer, then processed by the **execution environment**, which updates the state of the canisters on the replicated state machine and generates outputs, and these outputs are processed by the **message routing** layer.

It is useful to distinguish between two types of inputs:

ingress messages: these are messages from external users;

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cross-subnet messages: these are messages from canisters on other subnets.

We can also distinguish between two types of outputs:

ingress message *responses*: these are responses to ingress messages (which may be retrieved by external users);

cross-subnet messages: these are messages to canisters on other subnets.

Upon receiving a payload from consensus, the inputs in that payload are placed into various **input queues**. For each canister C running on a subnet, there are several input queues — there is one queue specifically for ingress messages to C, and each other canister C', with whom C communicates, gets its own queue. (In the case where C' is not located on the same subnet as C, these are cross-subnet messages.) As described below in more detail, in each round, the execution layer will consume some of the inputs in these queues, update the replicated state of the relevant canisters, and place outputs in various **output queues**. For each canister C running on a subnet, there are several output queues — each other canister C', with whom C communicates, gets its own queue. (In the case where C' is not located on the same subnet as C, these are cross-subnet messages.) The message routing layer will take the messages in these output queues and place them into **subnet-to-subnet streams** to be processed by a **crossnet transfer protocol**, whose job it is to actually transport these messages to other subnets.

In addition to these output queues, there is also an **ingress history** data structure. Once an ingress message has been processed by a canister, a **response** to that ingress message will be recorded in this data structure. At that point, the external user who provided the ingress message will be able to retrieve the corresponding response. (Note that *ingress history* does not maintain the full history of all ingress messages.)

We also should mention that in addition to cross-subnet messages, there are also **intra-subnet messages**, which are messages from one canister to another *on the same subnet*. The message routing layer moves such messages directly from output queues to corresponding input queues.

Figure 3 illustrates the basic functionality of the message routing and execution layers.

Note that the replicated state comprises the state of the canisters, as well as "system state", including the above-mentioned queues and streams, as well as the *ingress history* data structure. Thus, both the message routing and execution layers are involved in updating and maintaining the replicated state of a subnet. It is essential that all of this state is updated in a completely *deterministic* fashion, so that all replicas maintain *exactly* the same state.

Also note that the consensus layer is decoupled from the message routing and execution layers, in the sense that any forks in the consensus blockchain are resolved before their payloads are passed to message routing, and in fact, consensus does not have to keep in lock step with message routing and consensus and is allowed to run a bit ahead.

6.1 Per-round certified state

In each round, *some* of the state of a subnet will be *certified*. The **per-round certified state** is certified using chain-key cryptography (see Section 1.6), specifically, using the

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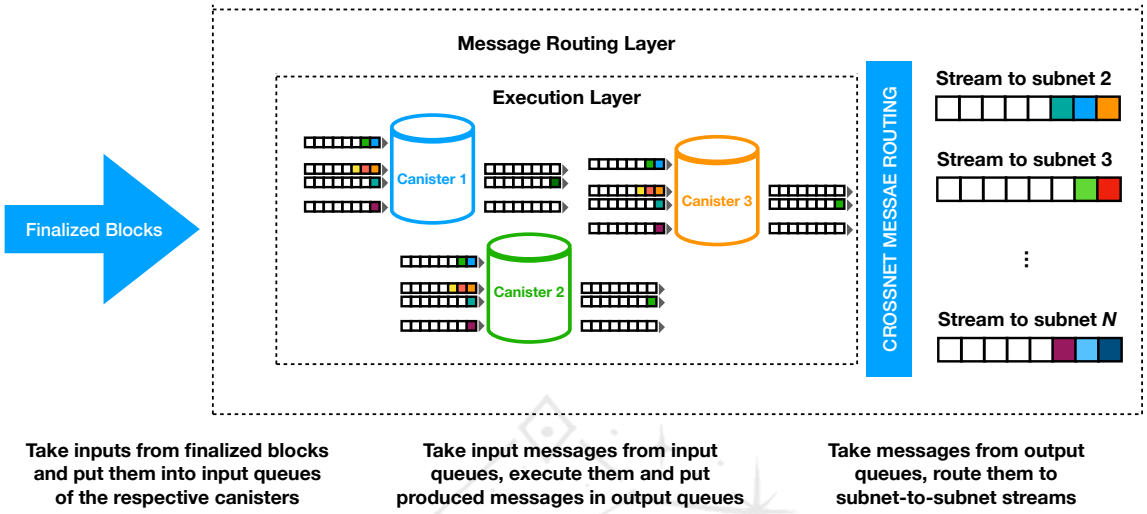


Figure 3: Message routing and execution layers

$(n - f)$-out-of-n threshold signature scheme mentioned in Section 3. In more detail, after each replica generates the per-round certified state for a given round, it will generate a share of the corresponding threshold signature and broadcast this to all other replicas in its subnet. Upon collecting $n - f$ such shares, each replica can construct the resulting threshold signature, which serves as the **certificate** for the per-round certified state for that round. Note that before signing, the per-round certified state is hashed as a **Merkle tree** [Mer87].

The *per-round certified state* in a given round consists of

1. *cross-subnet messages* that were recently added to the subnet-to-subnet streams;
2. other metadata, including the *ingress history* data structure;
3. the *Merkle-tree root hash* of the per-round certified state from the previous round.

Note that the per-round certified state does *not* include the entire replicated state of a subnet, as this in general will be quite huge and it would be impractical to certify *all* of this state in *every* round.[5]

Figure 4 illustrates how the per-round certified state may be organized into a tree. The first branch of the tree stores various metadata about each canister (but not the entire replicated state of the canister). The second branch stores the *ingress history* data structure. The third branch stores information about the subnet-to-subnet streams, including a "window" of recently added cross-subnet messages for each stream. The other branches store other types of metadata, not discussed here. This tree structure may then be hashed into a Merkle tree, which has essentially the same size and shape as this tree.

Per-round certified state is used in several ways in the IC:

[5]But see Section 8.2

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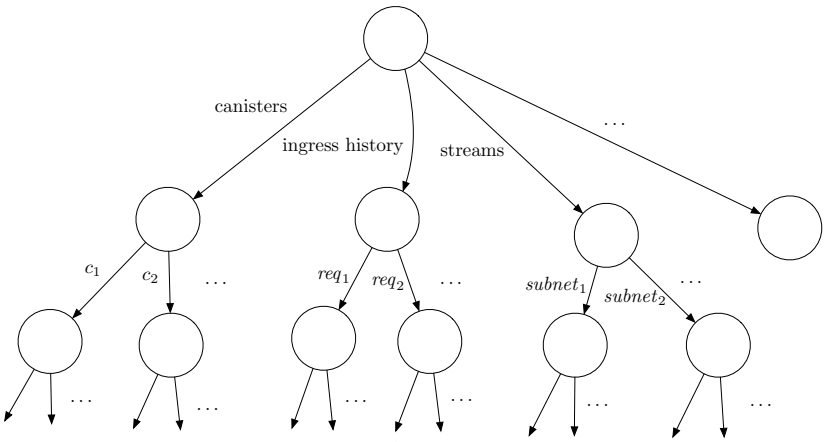


Figure 4: Per-round certified state organized as a tree

- **Output authentication.** Cross-subnet messages and responses to ingress messages are authenticated using per-round certified state. Using the Merkle tree structure, an individual output (cross-subnet message or ingress message response) may be authenticated to any party by providing a threshold signature on the root of the Merkle tree, along with hash values on (and adjacent to) the path in the Merkle tree from the root to the leaf representing that output. The number of hash values needed to authenticate an individual output is therefore proportional to the *depth* of the Merkle tree, which is typically quite small, even if the *size* of the Merkle tree is very large. Thus, a single threshold signature can be used to efficiently authenticate many individual outputs.

- **Preventing and detecting non-determinism.** Consensus guarantees that each replica processes inputs in the same order. Since each replica processes these inputs deterministically, each replica should obtain the same state. However, the IC is designed with an extra layer of robustness to prevent and detect any (accidental) non-deterministic computation, should it arise. The per-round certified state is one of the mechanisms used to do this. Since we use an $(n-f)$-out-of-n threshold signature for certification, and since $f < n/3$, there can only be one sequence of states that is certified.

  To see why state chaining is important, consider the following example. Suppose we have 4 replicas, P_1, P_2, P_3, P_4, and one is corrupt, say P_4. Each of the replicas P_1, P_2, P_3 start out in the same state.

  – In round 1, because of a non-deterministic computation, P_1, P_2 compute a message m_1 to send to subnet A, while P_3 computes a message m_1' to send to subnet A.

  – In round 2, P_1, P_3 compute a message m_2 to send to subnet B, while P_2 computes a message m_2' to send to subnet B.

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– In round 3, P_2, P_3 compute a message m_3 to send to subnet C, while P_1 computes a message m'_3 to send to subnet C.

This is illustrated in the following table:

$$\begin{array}{llll} P_1 & m_1 \to A & m_2 \to B & m'_3 \to C \\ P_2 & m_1 \to A & m'_2 \to B & m_3 \to C \\ P_3 & m'_1 \to A & m_2 \to B & m_3 \to C \end{array}$$

We are assuming that replicas P_1, P_2, and P_3 each individually perform a *valid* sequence of computations, but that because of non-determinism, these sequences are not identical. (Even though there is not supposed to be any non-determinism, in this example, we are supposing that there is.)

Now suppose we did not chain the states. Because P_4 is corrupt and may sign anything, he could create a 3-out-of-4 signature on a round-1 state that says "$m_1 \to A$", and similarly on a round-2 state that says "$m_2 \to B$", and on a round-3 state that says "$m_3 \to C$", *even though the corresponding sequence*

$$m_1 \to A,\ m_2 \to B,\ m_3 \to C$$

may not be compatible with ***any*** *valid sequence of computations.* Worse yet, such an invalid sequence of computations could then lead to inconsistent states on other subnets.

By chaining, we ensure that even if there is some non-determinism, any sequence of certified states corresponds to *some* valid sequence of computations that was actually carried out by honest replicas.

- **Coordination with consensus.** The per-round certified state is also used to coordinate the execution and consensus layers, in two different ways:
  - *Consensus throttling.* Each replica will keep track of the latest round for which it has a certified state — this is called the **certified height**. It will also keep track of the latest round for which it has a notarized block — this is called the **notarized height**. If the notarized height is significantly greater than the certified height, this is a signal that execution is lagging consensus, and that consensus needs to be *throttled*. This lagging could be due to non-deterministic computation, or it could just be due to a more benign performance mismatch between the layers. Consensus is throttled by means of the *delay functions* discussed in Section 5.9 — specifically, each replica will increase the "governor" value ϵ as the gap between notarized height and certified height grows (this makes use of the notion of "locally adjusted delay functions, as in Section 5.12.2).
  - *State-specific payload validation.* As discussed in Section 5.7, the inputs in a payload must pass certain validity checks. In fact, these validity checks may depend to a certain degree on the state. A detail we skipped is that each block includes a round number, with the understanding that these validity checks should be made with respect to the certified state for that round number. A replica that

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needs to perform this validation will wait until the state for that round number has been certified, and then use the certified state for that round to perform the validation. This ensures that even with non-deterministic computation, all replicas are performing the same validity tests (as otherwise, consensus could get stuck).

6.2 Query calls vs update calls

As we have described it so far, ingress messages must pass through consensus so that they are processed in the same order by all replicas on a subnet. However, an important optimization is available to those ingress messages whose processing does not modify the replicated state of a subnet. These are called **query calls** — as opposed to other ingress messages, which are called **update calls**. Query calls are allowed to perform computations which read and possibly update the state of a canister, but any updates to the state of a canister are never committed to the replicated state. As such, a query call may be processed directly by a single replica without passing through consensus, which greatly reduces the latency for obtaining a response from a query call.

Note that a response to a query call is not recorded in the *ingress history* data structure. As such, we cannot directly use the per-round certified state mechanism to authenticate responses to query calls. However, a separate mechanism for authenticating such responses is provided: **certified variables**. As a part of the per-round certified state, each canister on a subnet is allocated a small number of bytes, which is the *certified variable for that canister*, whose value may be updated via update calls, and may be authenticated using the per-round certified state mechanism. Moreover, a canister may use its certified variable to store a root of a Merkle tree. In this way, a response to a query call to a canister may be authenticated so long the response is a leaf in the Merkle tree rooted at the certified variable for that canister.

6.3 External user authentication

One of the main differences between an ingress message and a cross-subnet message is the mechanism used for authenticating these messages. We have already seen above (see Section 6.1) how threshold signatures are used to authenticate cross-subnet messages. The NNS registry (see Section 1.5) holds the public verification keys for the threshold signatures used to authenticate cross-subnet messages.

There is no central registry for external users. Rather, an external user identifies himself to a canister using a **user identifier** (aka *principal*), which is a hash of a public signature-verification key. The user holds a corresponding secret signing key, which is used to sign ingress messages. Such a signature, as well as the corresponding public key, is sent along with the ingress message. The IC automatically authenticates the signature and passes the user identifier to the appropriate canister. The canister may then authorize the requested operation, based on the user identifier and other parameters to the operation specified in the ingress message.

First-time users generate a key pair and derive their user identifier from the public key during their first interaction with the IC. Returning users are authenticated using the secret key that is stored by the user agent. A user may associate several key pairs with a single

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user identity, using signature delegation. This is useful, as it allows a single user to access the IC from several devices using the same user identity.

7 Execution Layer

The execution environment processes one input at a time. This input is taken from one of the input queues, and is directed to one canister. Based on this input and the state of the canister, the execution environment updates the state of the canister, and additionally may add messages to output queues and update the *ingress history* (possibly with a response to an earlier ingress message).

In a given round, the execution environment will process several inputs. A **scheduler** determines which inputs are executed in a given round, and in which order. Without going into all the details of the scheduler, we highlight some of the goals:

- it must be *deterministic*, i.e., only depend on the given data;
- it should distribute workloads *fairly* among canisters (but optimizing for *throughput* over *latency*).
- the total amount of work done in each round, measured in terms of *cycles* (see Section 1.8), should be close to some pre-determined amount.

Another task that the execution environment (together with the message router) must deal with are situations where a canister on one subnet is producing cross-subnet messages faster than they can be consumed by a canister on another subnet. For this, a self-regulating mechanism is implemented that *throttles* the producing canister.

There are many other resource management and bookkeeping tasks that are dealt with by the execution environment. However, all of these tasks must be dealt with *deterministically.*

7.1 Random tape

Each subnet has access to a **distributed pseudorandom generator (PRG)**. As mentioned in Section 3, pseudorandom bits are derived from a seed that itself is an $(f+1)$-out-of-n BLS signature, called the **Random Tape**. There is a different Random Tape for each round of the consensus protocol. While this BLS signature is similar to that used for the Random Beacon used in consensus (see Section 5.5), the mechanics are somewhat different.

In the consensus protocol, as soon as a block at height h is finalized, each honest replica will release its share of Random Tape for height $h+1$. This has two implications:

1. Before a block at height h is finalized by any honest replica, the Random Tape at height $h+1$ is guaranteed to be unpredictable.
2. By the time a block at height $h+1$ is finalized by any honest replica, that replica will typically have all the shares it needs to construct the Random Tape at height $h+1$.

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To obtain pseudorandom bits, a subnet must make a request for these bits. Such a pseudorandom-bit request will be made as a "system call" from the execution layer in some round, say h. The system will then respond to that request later, when the Random Tape of height $h + 1$ is available. By property (1) above, it is guaranteed that the requested pseudorandom bits are unpredictable at the time the request is made. By property (2) above, the requested random bits will typically be available at the time the next block is finalized. In fact, in the current implementation, at the time a block of height h is finalized, the Consensus Layer (see Section 5) will deliver both (the payload of) the block of height h and the Random Tape of height $h + 1$ simultaneously to the message routing layer for processing.

8 Chain-key cryptography II: chain-evolution technology

As mentioned in Section 1.6.2, chain-key cryptography includes a collection of technologies for robustly and securely maintaining a blockchain-based replicated state machine over time, which together form what is called **chain-evolution technology**. Each subnet operates in **epochs** of many rounds (typically on the order of a few hundreds of rounds). Chain-evolution technology implements many essential maintenance activities that are executed periodically with a cadence that is tied to epochs: *garbage collection*, *fast forwarding*, *subnet membership changes*, *pro-active resharing of secrets*, and *protocol upgrades*.

There are two essential ingredients to chain-evolution technology: **summary blocks** and **catch-up packages (CUPs)**.

8.1 Summary blocks

The first block in each epoch is a **summary block**. A summary block contains special data that will be used to manage the shares of the various threshold signature schemes (see Section 3). There are two threshold schemes:

- one $(f + 1)$-out-of-n scheme, for which a new signing key is generated every epoch;
- one $(n - f)$-out-of-n scheme, for which the signing key is *reshared* once every epoch.

The low-threshold scheme is used for the *random beacon* and the *random tape*, while the high-threshold scheme is used to certify the replicated state of the subnet.

Recall that the DKG protocol (see Section 3.5) requires that for each signing key, we have a set of dealings, and that each replica can non-interactively obtain its share of the signing key from this set of dealings.

Also recall that NNS maintains a **registry** that, among other things, determines the membership of a subnet (see Section 1.5). The registry (and hence the subnet membership) may change over time. Thus, subnets must agree on which **registry version** they use at various times for various purposes. This information is also stored in the summary block.

The summary block for epoch i contains the following data fields.

- *currentRegistryVersion*. This registry version will determine the *consensus committee* used throughout epoch i — all tasks performed by the consensus layer (block making, notarization, finalization) will be performed by this committee.

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- *nextRegistryVersion*. In each round of consensus, a block maker will include in its proposal the latest registry version it knows about (which must be no earlier than the block the proposed block extends). This ensures that the value *nextRegistryVersion* in the summary block of epoch i is fairly up to date.

  The value of *currentRegistryVersion* in epoch i is set to the value of *nextRegistryVersion* in epoch $i-1$.

- *currentDealingSets*. These are the dealing sets that determine the threshold signing keys that will be used to sign messages in epoch i.

  As we will see, the *threshold signing committee* for epoch i (i.e., the replicas that hold the corresponding threshold signing key shares) is the *consensus committee* for epoch $i-1$.

- *nextDealingSets*. This is where dealings that are *collected* during epoch $i-1$ are gathered and stored.[6] The value of *currentDealingSets* in epoch i will be set to the value of *nextDealingSets* in epoch $i-1$ (which itself consists of dealings collected in epoch $i-2$).

- *collectDealingParams*. This describes the parameters that define the dealing sets to be *collected* during epoch i. During epoch i, block makers will include dealings in their proposed blocks that are validated relative to these parameters.

  The *receiving committee* for these dealings is based on the *nextRegistryVersion* value of the summary block of epoch i.

  For the low-threshold scheme, the *dealing committee* is the *consensus committee* for epoch i.

  For the high-threshold scheme, the shares to be reshared are based on the value of *nextDealingSets* of epoch i. Therefore, the *dealing committee* is the *receiving committee* for epoch $i-1$, which is also the *consensus committee* for epoch i .

  Also observe that the *threshold signing committee* for epoch i is the *receiving committee* in epoch $i-2$, which is the *consensus committee* for epoch $i-1$.

Consensus in epoch i relies on the values *currentRegistryVersion* and *currentDealingSets* in epoch i — in particular, the makeup of the consensus committee itself is based on *currentRegistryVersion* and the random beacon used in consensus is based on *currentDealingSets*. Moreover, just like any other block, there could be more than one summary block notarized at the beginning of epoch i, and that ambiguity needs to be resolved by consensus in epoch i. This seeming circularity is resolved by insisting that a summary block at the beginning of epoch $i-1$ has been finalized before epoch i starts, since the relevant values in the newer summary block are copied directly from that older summary block. This is actually an *implicit synchrony assumption*, but it is quite an academic assumption. Indeed, because of the "consensus throttling" discussed in Section 5.12.2 to ensure liveness, and because of

[6] A detail we have omitted is that if we fail to collect all the required dealings in epoch $i-1$, then as a fallback, the value of *nextDealingSets* in epoch i will effectively be set to the value of *currentDealingSets* in epoch i. If this happens, then the protocol will make use of *dealing committees* and *threshold signing committees* from further in the past, as appropriate.

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the length of an epoch is quite large, this can essentially never happen in practice: long before consensus could reach the end of epoch $i-1$ without finalizing a summary block for epoch $i-1$, the notarization delay function would grow to be astronomically large, and so the partial synchrony assumption needed for finalization will be satisfied (essentially) with certainty (for all practical purposes).[7]

8.2 CUPs

Before describing a CUP, we first point out one detail of random beacon: the random beacon for each round depends on the random beacon for the previous round. This is not an essential feature, but it impacts the design of the CUP.

A **CUP** is a special message (not on the blockchain) that has (mostly) everything a replica needs to begin working in a given epoch, without knowing anything about previous epochs. It consists of the following data fields:

- The root of a Merkle hash tree for the *entire* replicated state (as opposed to the partial, per-round certified state as in Section 6.1).
- The summary block for the epoch.
- The random beacon for the first round of the epoch.
- A signature on the above fields under the $(n-f)$-out-of-n threshold signing key for the subnet.

To generate a CUP for a given epoch, a replica must wait until the summary block for that epoch is finalized and the corresponding per-round state is certified. As already mentioned, the *entire* replicated state must be hashed as a Merkle tree — even though a number of techniques are used to accelerate this process, this is still quite expensive, which is why it is only done once per epoch. Since a CUP contains only the root of this Merkle tree, a special **state sync** subprotocol is used that allows a replica to pull any state that it needs from its peers — again, a number of techniques are used to accelerate this process, but it is still quite expensive. Since we are using a high-threshold signature for a CUP, we can be sure that there is only one valid CUP in any epoch, and moreover, there will be many peers from which the state may be pulled. Also, since the public key of the threshold signature scheme remains constant over time, the CUP can be validated without knowing the current participants of the subnet.

8.3 Implementing chain-evolution technology

Garbage collection: Because of the information contained in a CUP for a given epoch, it is safe for each replica to purge all inputs that have been processed, and all consensus-level protocol messages needed to order those inputs, prior to that epoch.

[7] Also note that dealings that are collected in epoch i depend on data in the summary block for epoch i, in particular, the values of *nextDealingSets* and *nextRegistryVersion* . As such, these dealings should not be generated and cannot be validated until a summary block for epoch i has been finalized.

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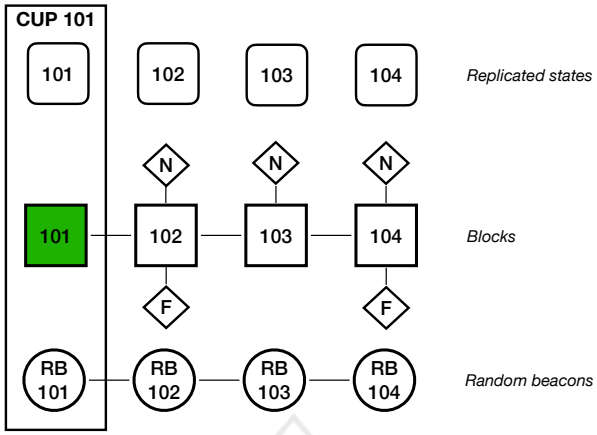


Figure 5: Fast forwarding

Fast forwarding: If a replica in a subnet falls very far behind its peers (because it is down or disconnected from the network for a long time), or a new replica is added to a subnet, it can be *fast forwarded* to the beginning of the most recent epoch, without having to run the consensus protocol and process all of the inputs up to that point. Such a replica may do so by obtaining the most recent CUP. Using the summary block and random beacon contained in the CUP, along with protocol messages from other replicas (which have not yet been purged), this replica may run the consensus protocol forward from the beginning of the corresponding epoch. The replica will also use the state sync subprotocol to obtain the replicated state corresponding to the beginning of the epoch, so that it may also process the inputs generated by consensus.

Figure 5 illustrates fast forwarding. Here, we assume that a replica that needs to catch up has a CUP at the beginning of an epoch, which starts (say) at height 101. The CUP contains the root of the Merkle tree for the replicated state at height 101, the summary block at height 101 (shown in green), and the random beacon at height 101. This replica will use the state sync subprotocol to obtain from its peers the full replicated state at height 101, using the root of the Merkle tree in the CUP to validate this state. Having obtained this state, the replica can then participate in the protocol, obtaining from its peers blocks (and other messages associated with consensus) at heights 102, 103, and so on, and updating its copy of the replicated state. If its peers have already finalized blocks at greater heights, this replica will process those finalized blocks as quickly as it can obtain them (and their notarizations and finalizations) from its peers (and as quickly as the execution layer will allow).

Subnet membership changes: We have already discussed how summary blocks are used to encode which version of the registry is in force in a given epoch, and how that is used to determine the subnet membership, and more specifically, the membership committees for various tasks. Note that even after a replica is removed from a subnet, it should (if possible) participate in its assigned committee duties for one additional

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epoch.

Pro-active resharing of secrets: We have already discussed how summary blocks are used to generate and reshare signing keys. If necessary, the required summary block may be obtained from a CUP.

Protocol upgrades: CUPs are also used to implement protocol upgrades. Protocol upgrades are initiated by the NNS (see Section 1.5). The basic idea, without going into all the details, is this:

- when it is time to install a new version of the protocol, the summary block at the beginning of an epoch will indicate this;
- the replicas running the old version of the protocol will continue running consensus long enough to finalize the summary block and to create a corresponding CUP; however, they will create only empty blocks and not pass along any payloads to message routing and execution;
- the new version of the protocol will be installed, and the replicas running the new version of the protocol will resume running the full protocol from the above CUP.

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