Towards a Contract Service Provider Model for Virtual Assets and VASPs

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Abstract

We introduce the contract service provider (CSP) model as an analog of the successful Internet ISP model. Our exploration is motivated by the need to seek alternative blockchain service-fee models that departs from the token-for-operations (gas fee) model for smart contracts found on many popular blockchain platforms today. A given CSP community consisting of multiple CSP business entities (VASPs) form a contract domain which implement well-defined contract primitives, policies and contract-ledger. The nodes of the members of CSP community form the blockchain network. We discuss a number of design principles borrowed from the design principles of the Internet Architecture, and we discuss the interoperability of cross-domain (cross-chain) transfers of virtual assets in the context of contract domains.

Keywords: Blockchains, smart contracts, virtual assets, contract service providers, contract domains.
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1 Introduction

The recent rise in the cost of transactions on Bitcoin and Ethereum illustrates the reality that the virtual asset industry is still in its nascency and that further consideration needs to be placed on the long-term feasibility of the tokenized operations model (i.e. gas fee model). The gas-fee model has a number of unintended side effects, including platform capture of end-users, unsafe smart contracts and the lack of incentives to solve the blockchain interoperability problem [1, 2].

In this paper we explore the notion of a contract service provider (CSP) model as an analog of the decades-old Internet Service Provider (ISP) model that has enabled the Internet to expand and flourish. Our CSP model is driven by a number of design principles that borrow from the design principles of the Internet Architecture [3, 4]. We discuss these design principles towards the end of the paper in order to first discuss the CSP model.

We seek to make the paper readable to a wide audience, and as such have sought to limit the usage of technical jargon. However, we assume the reader is at least familiar with Bitcoin, cryptocurrencies, and distributed ledgers generally.

2 Contract Service Providers: Motivations

A Contract Service Provider (CSP) is a regulated service provider who collaborates with other CSPs in making available on distributed nodes one or more smart contract primitives that consists of simple operations applicable to certain virtual assets issued by an authoritative legal entity. Collectively, the group of CSPs offers contract services to one or more regulated customers, which may include individuals and organizations. The contract primitives and the supported types of assets are chosen by the CSPs prior to deployment, and the set of primitives are not user-programmable. The goal of the contract service is to execute fixed set of functions on virtual assets, as invoked by the customers of the CSPs. As such, the CSP paradigm is similar to the Function as a Service (FaaS) model [5].

There are number of motivations for the contract service paradigm:

- **Alternative fee-for-service business model**: The contract service model provides an opportunity for a classic fee-for-service model for processing transfers of different types of regulated virtual assets. Since the primitives are simple and since the blockchain is not user-programmable, there is a deterministic and predictable cost for a service provider to participate in a CSP group. The CSPs determine the operating rules of the community, the amount of computing resources each CSP must put forward, and the CSPs can monitor each other with regards to the performance of the contractual obligations of members of the CSP community.

This approach is a departure from the gas fee model used in the Ethereum platform [6] where the price of the Ether has been shown to fluctuate dramatically depending on the popularity of certain contracts (e.g. DeFi [7, 8]) and where the overall throughput of the blockchain may be affected by popular contracts (e.g. CryptoKitty [9, 10]).
that negatively influence the availability of other contracts unrelated to the popular contracts.

- **Reduction of fees by separation of business logic from contract primitives**: Enabling end-users to freely program complex code logic directly on the blockchain nodes using a fully-fledged object language (e.g. Solidity [11]) fulfills the intended goal of many platform providers, namely *platform capture* of customers. The more complex the code logic, the more operations consumed and the higher the total gas fees obtained overall by the platform owners. However, as the fees climb higher this encourages Ponzi-like schemes where new entrants boost the profits of existing participants by driving demand for tokens [12].

Platform capture disincentivize interoperability of blockchain networks, and results in delays in the broad adoption of smart contracts technologies by the financial sector. Other negative side effects of on-chain complex code designs is the higher likelihood of human error and intentional abusive programming (e.g. DAO Hack due to reentrancy vulnerabilities [13, 14, 15]).

- **Support for interoperability across blockchain systems**: The use of simple contract primitives for specific types of assets generally lends itself more readily for interoperability of blockchain systems. When two blockchain systems employ semantically equivalent constructions of contract-primitives – albeit using different syntaxes (different programming languages) – with their ledgers capturing comparable data structures representing similar transactional behaviors, this results in the higher likelihood of business interoperability across blockchain systems based on technical interoperability.

## 3 Overview of Design Principles and Terminology

The following is a summary of the terminology we use in the current work, with further expansion in the following sections:

- **Contract Service**: Smart contract services defined by the set of primitive operations implemented on-chain and the asset-types processed through the primitives.

- **Contract Service Provider (CSP)**: A regulated service provider (e.g. registered business) that participates in making available contract services to its customers.

- **CSP Community**: A group of CSPs offering contract services on a blockchain network consisting of their nodes.

- **Contract Domain**: The various computing resources required to implement a contract service, including contract-specific functional components (i.e. primitives, contract-ledger, consensus algorithm and domain policies) and the other technological constructs that implement the domain.
• **Virtual Asset Service Provider (VASP):** Entity dealing with virtual assets covered under the FATF definition for virtual assets and the Travel Rule (see [16][17]).

The contract service provider (CSP) model is based on the following design principles that take into account code complexity considerations and the provider’s deployment considerations:

(a) **Contract simplicity principle:** Each smart contract should implement a simple and modular well-defined function, following classic object-oriented design principles. This is also referred to as the *decentralized primitives* principle.

(b) **Constrained authorship principle:** Each contract must be made available only by a contract service provider (CSP) entity within the group of CSPs.

(c) **Node diversity principle:** A contract service blockchain network must employ a diverse node-technology implementations and be owned/operated by a diverse set of providers.

(d) **Mediated oracle principle:** Any representation of value that originates from outside the contract service (contract domain) must enter (be introduced) into the contract service through the mediation of a contract service provider.

(e) **Opaque ledgers assumption:** Any cross-chain or cross-domain asset transfer protocol must be designed based on the assumption that the ledgers of the respective blockchains are not externally readable/writeable.

We discuss the design principles in more detail in Section 7.

### 4 Contract Service and CSP Communities

We define a *CSP community* as a group of regulated contract service providers offering asset-related smart contract services on a blockchain network whose nodes are composed of the computing resources of the members of the CSP community. The notion of a community is contract-centric in that the CSPs in a community agree to allocate computing resources for a given smart contract service. A given CSP community may be constituted to provide contract services for a single smart contract or for several related smart contracts on the same blockchain network. A **contract service** is defined by the set of **contract primitives** implemented on-chain and the **asset-types** processed through those primitives. An entity (individual or organization) is considered to be a regulated customer of a CSP by virtue of purchasing access to the smart contract services through that CSP. For a given contract service, an entity should be a customer of one CSP only in the CSP community. The CSP community must clearly define beforehand the contract primitives and the asset-types that constitute the contract-service, in order to prevent confusion on the part of customers.

From a legal perspective, a CSP community must be founded on a legal contractual agreement that defines the obligations and liabilities of each of the members to the community.
Figure 1: Simple example of three (3) CSP communities viewed from a contract-centric perspective

and to the customers of members. The community defines a service level agreement (SLA) for the customers of the members. This approach is akin to multi-lateral peering agreements used by Internet Service Providers (ISPs), which defines common data routing responsibilities across multiple networks.

A simple example of three (3) CSP communities is shown in Figure 1. Community C1 are CSPs providing contract service SCS1, the Community C2 providing contract service SCS2, while Community C3 the contract service SCS3. The CSP X is active in all three communities, where in each case it makes available computing resources (nodes) to each community. In two cases (the intersection areas of Figure 1) the CSP X is using contract multi-tenancy on the same nodes.

4.1 The Contract Domain

We use the notion of the contract domain in order to reason more accurately about the various technical and implementation aspects of a contract service, including access to the components of the contract service (e.g. contract calling APIs, ledger, etc). A contract domain is defined by a CSP community through a combination of the following: (i) the set of contract-primitives that constitute the contract service together with the contract ledger and consensus algorithm for the ledger; (ii) the policies regarding the asset types permitted to be transacted in the jurisdiction of operation of the CSP community; (iii) the nodes infrastructure that implements the contract-primitives and enforces policies. This is shown in Figure 2. For simplicity, we use the term domain functions in a domain to refer to the technical components (i.e. contract-primitives, contract-ledger, consensus algorithm and domain policies) and the other technological constructs that implement the domain (e.g. membership management, asset validation, etc).

A contract domain coincides with the CSP community in that both represent the same
Figure 2: Overview of a contract domain

participating business entities (e.g. CSPs) and the resources (i.e nodes) dedicated by the business entities to establish the contract service. Thus, for business reasons a given CSP entity may be member of different CSP communities simultaneously at any given moment, where it allocates the computing resources required for each community (e.g. minimal $M$ nodes). In each community, the contract domain structure ensures that a separate ledger and consensus mechanism is used to record the asset transactions in that contract domain. Figure 3 illustrates a case in which some CSPs are participating in several contract domains simultaneously. For example, CSP-A is participating contract-domains CD1, CD2 and CD3, while CSP-C is participating in domains CD2 and CD3 only. This means that CSP-A, CSP-B and CSP-C share a common contract-ledger for CD3 and jointly participate in the consensus mechanism to maintain that contract-ledger. The CSP-A, CSP-C and CSP-D a common contract-ledger for domain CD2.

There are several aspects worth noting about a contract domain and the resources (nodes) implementing the contract domain:

- **Per contract-domain consensus algorithm and decentralized ledger**: The nodes that implement the contract service in a domain employ a separate consensus algorithm and contract-ledger specifically for that the contract service. The choice of consensus algorithm and form of the ledger blocks is defined by the CSP community through their formative the legal agreements.

Thus, in Figure 3 there is a separate ledger for contract service SCS1, SCS2 and SCS3. The provider CSP A participates in maintaining three (3) separate ledger for each of these three contract-domains.

- **Opaque ledgers and contracts to non-customers**: When a customer obtains services from

| Contract Domain | (M nodes min.) | (M nodes min.) | (M nodes min.) | (M nodes min.) |
|-----------------|----------------|----------------|----------------|----------------|
| Contract Primitives | Contract Primitives | Contract Primitives | ... | Contract Primitives |
| Contract Ledger | Contract Ledger | Contract Ledger | ... | Contract Ledger |
| Consensus Algorithm | Consensus Algorithm | Consensus Algorithm | ... | Consensus Algorithm |
| Domain Policies | Domain Policies | Domain Policies | ... | Domain Policies |

Figure 2: Overview of a contract domain
a CSP who is a member of a CSP community, the customer has visibility only into the relevant resources (e.g. contract ledger) for that CSP community. This follows from the opaque ledgers principle (described below in Section 7.5). A given CSP may participate (i.e. dedicate nodes) in multiple CSP-communities (contract domains), each of which deploys a distinct consensus algorithm and ledger.

Using Figure 3, if a customer of CSP-A purchases access to contract-service SCS3 (domain CD3), the customer has visibility only to the ledger for SCS3 (i.e. no access to ledgers for SCS1 and SCS2).

In the remainder of this paper, we will use the term “CSP community” when discussing the business and legal aspects of contract services by a CSP, and we shall use “contract domains” when discussing the technical aspects of the contracts, nodes, ledgers and blockchain.

4.2 Primitives in a Contract Service

The goal of the simple primitives principle is to ensure that smart contract services implement simple primitive functions that can be used by (i.e. called by) higher layer applications that contains the complex business logic. Although there are several possible primitives that a contract-service may use, we believe the following represents the minimal primitives which must be implemented in a contract domain:

- **Asset transfer from one customer to another**: This operation moves the ownership of a virtual asset from one customer to a second customer, both of which must have been previously onboard by a CSP in the community. This is equivalent to Bitcoin’s payment to public key (or to a hash of public key).
• **Asset escrow to another customer or to CSP**: This operation conditionally moves the ownership of a virtual asset from one customer to another, or to a CSP in the community.

The choice of which the escrow CSP is determined by the operating rules of the CSP community (e.g. random choice). The escrows are time-limited, meaning that if the condition fails to be satisfied within the specified time, the asset reverts back to the customer.

• **Asset ingress into blockchain**: This operation introduces a regulated virtual asset into the contract domain, making it available to trade for customers. This event may be at the request of a customer of a CSP. This operation is available only to a CSP because the CSP must validate the legal status of the asset prior to introducing it into the contract domain. A customer cannot introduce virtual assets on their own.

• **Asset egress from blockchain**: This operation removes a regulated virtual asset from the contract domain, making it no longer available to customers. This operation is available only to a CSP. It marks the ledger to indicate that the asset has moved to another contract domain and therefore unavailable for further use.

Other contract primitives possible include those pertaining to key management and to different types of virtual assets. For example, the key management tasks include: introduction of a customer (new customer) public-key into the contract domain; key-rotation (or revocation) of customer’s public-key; introduction of a new CSP public-key; key-rotation (or revocation) of CSP’s public-key; and so on. Asset related tasks include: introduction of a new asset-type (e.g. new stablecoin, etc.), removal of an existing asset-type; and so on. These are beyond the current work and are dependent on the contract service and CSP community that implements the contract service.

### 4.3 CSP Community Membership Agreement

The computing resource to be allocated by each CSP in a CSP-community, the specifications of the technical mechanisms (e.g. protocols) to be used in the community, as well as other operational aspects of the contract domain is expressed in the CSP community membership agreement document, which is a legally binding contractual agreement. The specifications of the technical mechanisms for a given contract domain is referred to as the contract domain profile document.

The community membership agreement may also specify the number of CSP entities minimally required to implement the contract domain, and the methods to add or subtract the CSP membership. The agreement may also place a time duration commitment on CSPs, meaning that once a contract service is made operational by a CSP community the CSPs are bound to be a member (i.e. allocate nodes and computing resources) until the end of the duration.
From a revenue perspective, the CSP community membership agreement must specify the revenue sharing structure of the CSPs in that community. For example, for each new customer brought by a CSP entity, the CSP may be mandated to share a certain percentage of the fees paid that customer. Other revenue sharing models may be based on the number of transactions transmitted from customers of CSPs.

Although beyond the scope of the current work, the notion of a **nodes diversity index** could be defined in the CSP community membership agreement as a measure of the diversity of the node-implementation technologies [13]. The node diversity index may provide customers with a tangible indicator of the resiliency of the blockchain network as a whole.

### 4.4 Computing Resources for Nodes

One of the main decision factors for a CSP as a business entity is the amount of computing resources it needs to allocate to a contract domain. CSPs have the freedom to implement nodes using various technologies (e.g. bare metal computers; private cloud-based compute units; public-cloud hosted virtual machines, and so on). An example is shown in Figure 4. Certain contract domains (CSP communities) may require that the contract-ledger be readable/writeable only to other CSPs in the same contract domain (i.e. private contract-ledger), while other contract domains may require that the contract-ledger merely be member-writeable (but publicly readable). In choosing its node implementation strategy, a CSP must cognizant of these community specific requirements as describe in the CSP community membership agreement.

For a CSP it is useful to logically divide the functions and resources needed for the implementation of a contract domain following a layered architecture:

- **Contract primitives layer**: The constructs at this layer include the contract-code, public-keys, digital certificates, signed claims (regarding data sources) by CSPs, and others.

- **Transaction data layer**: The resources at this layer include CPU for processing transactions, storage for historical blocks of confirmed transactions, data sharding mechanisms [19] and other transaction-related events data.

- **Consensus mechanisms layer**: The resources at this layer include code implementations of the consensus mechanism chosen by the CSP community for the contract domain (e.g. Proof of Work [20], Proof of Stake [6 21], and others [22 23]).

- **Contract policies layer**: The constructs at this layer include the policies related to the contract domain and mechanisms implementing and enforcing these policies.

- **Node network layer**: The resources at this layer include IP network connectivity, discovery of nodes in the CSP community, topology management, new transaction propagation, and others.
• **Hardware identification and node attestations layer**: In this layer, hardware-related capabilities information are exposed to higher layer functions as a means to establish attestations by nodes [5, 24] regarding the trustworthiness of the node implementation.

Figure 4 provides a high level node-centric illustration of the various strategies CSPs may employ to realize a contract domain. The configuration (i) shows a “bare metal” implementation of a node where the CSP-A owns and operates the full stack. In configuration (ii) the CSP-B participates in two contract domains (CD1 and CD2) each associated with two distinct communities. In configuration (iii), the CSPs employ a third-party cloud provider that offers multi-tenancy.

### 4.5 Sources of Value for Virtual Assets: Issuers and Acquirers

The contract service provider model assumes that value associated with virtual assets originate from outside the contract domain, and that an authoritative legal entity has accorded a denominated value to a virtual asset prior to the asset being ingested into the contract domain (mediated by one or more CSPs in the domain). This philosophy is consistent with our stated motivations of exploring alternative fee-for-service models that does not rely on utility tokens for operations fee (i.e. gas fee), which has a number of downsides for customers [7, 8].

The method to determine the value of an asset is outside of the current work, and several mechanisms have been proposed (e.g. see [25, 26] for a proposed taxonomy).

The function of issuing virtual assets based on real-world assets or other denominational value is assumed to be performed by an asset **Issuer** authority. The function converting virtual assets into its denomination equivalent is assumed to be performed by an asset **Acquirer** authority. This assumption is consistent also with a number of exploratory projects that
Figure 5: Sources of value for virtual assets external to the contract-domain

have been reported (e.g. Project Ubin Phase-5 in Singapore [27]; Project Whitney at the DTCC [28, 29]).

Figure 5 presents two general use cases where two CSPs in two asset-compatible contract-domains (CD1 and CD2) are involved in the transfer of assets. In Figure 5(a) both CSP-A and CSP-X reside within the same legal jurisdiction J1 (e.g., same country) and therefore both CSPs can rely on the same issuer/acquirer of the virtual asset. When the virtual asset has been introduced into the contract-domain CD1, it is transferable within CD1 in the usual manner. When an asset is to be transferred cross-domain from CSP-A to CSP-X, the CSP-X can easily validate the legal status of the asset to the same issuer/acquirer because domains CD1 and CD2 are under the same jurisdiction J1. In Figure 5(b), the contracts domains CD1 and CD2 are under different jurisdictions J1 and J2 respectively. In this case, when an asset is to be transferred cross-domain from CSP-A to CSP-X, the CSP-X must rely on its local issuer/acquirer IA2. As such, the two issuer/acquirers (IA1 and IA2) must have a business and legal relationship that permits CSPs to query the status of virtual assets prior to transfers cross-domain.

The interaction model in Figure 5(b) is referred as the 4-corners model, and the term “issuer” and “acquirer” has been used for nearly two decades in the credit card payments industry. In the cards payment world, the consumer (card-holder) obtains a credit card from the Issuer, which is often also a bank or related financial institutions. When the customer uses the card at a merchant (e.g., to purchase goods at a Point of Service (POS) terminal) the merchant forwards the transactions details to the Acquirer, which is typically the merchant’s bank or financial institution. The Acquirer then obtains payment from the Issuer bank (e.g., debited from the customer’s bank account). This model is called the 4-corners payments model because of the four entities involved [30]. It has been very successful as evident from the global reach of the card payments industry. The 4-corners paradigm is useful in the
context of a contract domain because (i) it permits the CSP role to be separated from the role of asset Issuer/Acquirer, and (ii) it permits the notion of global jurisdictions to come into the picture by recognizing that the issuers of virtual assets may reside in different legal jurisdictions (countries), and different degrees of compliance to the Travel Rule.

5 Policies for the Contract Domain

Generally speaking, all computer systems and networks operate based on some “rules” or policies that maybe intrinsic to their design (e.g. hardware level instruction set), or defined by the user and/or administrator of the system (e.g. file access policies). This is also true of nodes in a blockchain network. In considering a node as a computer system composed of hardware and software components, it is helpful to view a node as compute unit made of logical layers. This separation of functions based on logical layers provides the context within which to reason about the “rules” or policies applicable to each layer. Each functional layer may have both non-configurable and configurable parameters, where the later that can be adjusted by the user/administrator.

In this section we focus on policies in the contract domain, focusing specifically on those that affect the execution of contracts. Without going into details of a policy state-machine model, the basic notion is that nodes in a contract domain must react (take action) with regards to changes in conditions, which may originate externally from the domain.

We use the term contract policies for rules pertaining to virtual assets and contract executions within a contract domain. These are rules that are inherent within a contract domain, but which can be triggered by conditions outside the contract domain. To prevent terminology confusion, we use the term community core operating rules in the sense of [31] for rules and policies that pertain to the operations of the node infrastructure that implement the contract domain by the CSP community. The core operating rules must be part of the CSP community membership agreement document (Section 4.3), which is a legally binding contractual agreement.

5.1 Types of Contract Policies in a Contract Domain

As described earlier, a key goal of the contract simplicity principle to establish a proper separation between primitive operations encoded in a contract from complex business logic (Section 7.1). In many cases, business logic become complex and intricate because it incorporates business policies relevant to the organization.

The following are some illustrative examples of policies arranged according to their condition/response categories:

- Policies regarding changes to the condition of virtual assets: These are the set of rules pertaining to actions to be taken by a CSP should there occur a change to the external status of virtual asset that is currently present within the contract domain.
Example of an external change to a virtual asset includes the Issuer going out of business or temporarily halting operations (e.g. Issuer under legal investigation). In this case, the contract domain that has customers holding this virtual asset may choose to also temporarily cease all transactions related to that virtual asset.

- **Policies regarding changes to the condition of customers**: These are the set of rules pertaining to actions to be taken by a CSP should a change occur to the status a customer.

  For example, a customer of a CSP may face legal issues that necessitate the customer’s assets in the contract domain being frozen temporarily. Faced with a legal notification from the relevant authority (e.g. SAR warrant) the CSP community may then temporarily suspend the customer’s account and/or issue an asset-lock on the customer’s assets on the contract-ledger (see Section 6.4).

- **Policies regarding changes to the condition of CSP membership in a community**: These are the set of rules pertaining to actions to be taken by a CSP in response to changes in the membership composition of its CSP community.

  For example, assuming that a CSP is a VASP under the Travel Rule [16], if a CSP has its VASP business license revoked by the relevant authorities then other CSPs in that community must respond as defined in the policies (e.g. ignore all new transactions and block-confirmations from the revoked CSP).

- **Policies regarding cross-domain transactions**: These are the set of rules pertaining to asset transfers involving an external contract domain.

  For example, a customer of a CSP may wish to have their virtual assets transferred out of the current contract-domain to a different contract-domain in a different CSP community. In cases such as this, the policies of the contract domain may require the asset to be temporarily suspended in contract domain until it has been successfully moved to the external contract-domain.

### 5.2 Core Operating Rules for CSP Communities

The *core operating rules* for a CSP community defines the rules of interaction of the nodes of the CSPs in the community across the functional layers of the nodes. As mentioned previously, we view the functional layers of a node’s resources to consist of the contract primitives layer, the transactions data layer, consensus layer, the network layer and the hardware identification and attestation layer (see Section 4.4).

Given the decentralized transaction processing model of many blockchain networks, it is necessary to view these core rules as being applied to *distributed resources* with *distributed policy enforcement* model. One key component of distributed policy enforcement is the set privileges parameters [32] that take into account the actors/roles, contract operations, asset types and jurisdictions.
Figure 6 attempts to illustrate this distributed policy enforcement model where the “policies” here are the core operating rules in the CSP community. The nodes as the endpoints which enforce the core rules must also be equipped to perform decision-making on their own – with an assumed regular synchronization to the central policy-administration point [33]. Thus, the nodes as endpoints must be equipped with both PDP and PEP capabilities (Policy Decision Point, and Policy Enforcement Point) [34, 35]. The core rules and subsequent updates to those rules must originate from the governance organization of the CSP community. In Figure 6, a centralized entity called the Policy Administration Point (PAP) for the contract domain distributes these rule-updates.

5.3 Policy-Driven Systems: A Brief History

The notion of policy-driven access control to resources is not a new idea, and has in fact evolved since the early days of the networked organizations over three decades ago. Traditional Enterprise IT infrastructures demarcate access to resources (e.g. file-servers, printers, network elements, etc.) through the notion of access control domains [36, 37]. Thus, all subjects, roles, objects (resources), actions, and rules (policies) are defined for the entities and the services that reside within the access control domain. Subjects with privileges in multiple domains are accorded different roles when accessing resources in those domains.

The differentiation between centralized and distributed networks is important from the perspective of the development of privileges architecture that govern access to resources accessible to participants in the network [38]. Within traditional enterprise networked systems, policy-driven access control evolved in enterprise organizations starting in the 1990s.
As shared resources (e.g., file servers) within an enterprise were made available within the network (i.e., Local Area Networks (LAN)), the issue of controlling access to these shared resources became increasingly crucial for the survival of the enterprise network, and the enterprise as a whole.

The access control model that became predominant in enterprise networks was the Bell and LaPadula Model (BLP) [39]. In this model, access control is defined in terms of subjects possessing different security levels, seeking access to objects (i.e., system resources). Thus, for example, in the BLP model a subject (e.g., user) is permitted to access an object (e.g., file) if the subject’s security level (e.g., “Top Secret”) is higher than security level of the object (e.g., “Secret”). The notion of roles or capacities was added to this model, leading to the Role-Based Access Control (RBAC) model. Here, as a further refinement of the BLP model, a subject (user) may have multiple roles or capacities within a given organization. Thus, when the subject is seeking access to an object, he or she must indicate the role within which the request is being made. The formal model for RBAC was defined by NIST in 1992 [40].

The same RBAC model applies also to corporate resources attached to the corporate LAN. Corporate security policies were therefore expressed in terms of access-control policies as applied to subjects in certain roles seeking access to objects residing within a given administrative domain. This problem was often referred to as Authentication, Authorization and Audit (AAA) in the 1990s [34]. Part of the AAA model developed during the 1990s was an abstraction of functions pertaining to deciding access rules, from functions pertaining to enforcing them. Entities which authored policies were referred to as Policy Administration Points (PAP), those who decided on access-rules were denoted as Policy Decision Points (PDP), while entities that enforced these access-rules were denoted as Policy Enforcement Points (PEP) [35]. This policy-based access control model is foundational to many systems deployed within enterprises today, where privileges management is performed typically through directory services (e.g., Microsoft Active Directory [41]) that maintains the list of valid employees of the enterprise. This approach is very common in mid to large organizations, including notably those in the financial industry.

6 Interoperability of Contract Domains

The notion of a CSP-community is based in the successful model of Internet Service Provider (ISP) communities, which implement a number of proven design principles of the Internet Architecture [3, 4]. Two of the fundamental principles are autonomous system (AS) principle and the end-to-end principle.

Each CSP-community implementing a contract domain is an autonomous system in the sense that the nodes of the CSPs can operate independently from other blockchain networks. The contract domain observes the end-to-end principle by externalizing the source of value of virtual assets to the end-points. Thus, the contract domain is oblivious to the value or monetary aspect of the virtual assets flowing within contract domain. This is in contrast to blockchain platforms that operate based on users purchasing tokens that are endogenous to
the blockchain [42], thereby effecting platform-capture for its users.

The Internet in reality is a “stitched” collection of islands of IP networks owned by ISPs, and they are able to interoperate at the technical level due to standardized protocols and interoperate at the business and legal level due to *peering agreements* (bilateral agreements and group-agreements). Similarly, CSP communities will need to develop peering agreements with other CSP communities in order for virtual assets to be able to enter and leave contract-domains in an efficient and regulated manner.

### 6.1 Cross-Domain Transfers: Basic Requirements

The constrained authorship principle (see Section 7.2) means that customers (end-users) are prohibited from publishing their own contracts onto the nodes of the contract domain. Only the CSPs in the group are permitted to author and publish the contract primitives. This has the advantage that control over a smart contract [43] is unambiguously in the hands of the publishing CSP in the CSP-community. This means that quality and safety of smart contracts is the clear responsibility of the CSP-community as whole. This, in turn, provides a sound basis to begin addressing the challenges around cross-domain asset transfers.

There are a number of functional requirements for cross-domain transfers of virtual assets between two contract-domains:

- **Asset validation before transfer**: There must be some means for the recipient entity (in the destination contract-domain) to validate the asset type and legal status prior to transfer.
engaging with the transfer. This function is represented as the asset attester/verifier function in Figure 5 and in Figure 7.

- **Commitment atomicity**: Cross-domain asset transfers must employ an atomic commitment scheme that prevents (detect) the same asset being present on two contract-domains (e.g., using 2-Phase Commit Protocol (2PC) [44, 45]). There are several efforts today to reuse the atomic commitment protocols from the field of distributed databases and concurrency control (e.g., see [46]). The overall aim of many of these schemes is to interpret (re-cast) the ACID properties (atomicity, consistency, isolation, durability) [47] of these protocols to the context of asset transfers, at least for unidirectional transfers (nb. database transactions are typically unidirectional). Additional properties (e.g., safety, liveness) have also been suggested (e.g., cross-chain deals [48]).

- **Transfer non-repudiability**: There must be sufficient evidence regarding the finality and settlement at both contract domains to obviate disputes by either a CSP or a customer (in one or both domains). Evidence of settlement can consist of the combinations of confirmed transactions on the blocks on both contract-ledgers, local signed-logs by the nodes handling the cross-domain transfer, logs from the commitment layer, and so on. Evidence needed for disputes between two CSP-communities must be specified in their peering agreement document.

- **Policy federation as part of peering agreements**: Contract domains need compatible policies along several axes, including: (i) the type of regulated asset being transferred; (ii) the legal jurisdiction of operations of the contract-domain; (iii) the type of operations permitted (e.g., unidirectional unconditional transfers only, conditional transfer, etc), (iv) the agreed commitment protocol and non-repudiation protocol to be used (or negotiated from a common standard list), and (v) the configuration of the nodes handling the transfers on both sides based on the node-device attestation evidence (see [24, 49] for a discussion on node device identities and node attestations).

- **Publication of peering-points**: Similar to BGP-routers in IP networks, a given CSP community implementing a contract-domain must determine the peering-points to be used in cross-domain asset transfers. The peering-points configuration and location (e.g., IP address and port-number) should part of the peering agreement. CSPs should generally standardize on a common notation and configuration for peering-points as it helps all CSPs to know the first port of call for remote (foreign) CSPs.

### 6.2 Gateway Nodes

The method used by a contract domain to select the node in the domain that will perform the cross-domain transfer is determined by the configuration rules in the domain’s core operational policies. Some consensus protocol (e.g., in the family of BFT protocols [23, 22])
implement a leader election mechanism that chooses one node out of the network to perform the designated computation (e.g. forging a block in Ethereum). In the context of asset transfers that involve an external or foreign contract-domain, we refer to that chosen node as the *gateway node*.

However, there are several possible strategies with regards to determining the gateway-nodes that will perform cross-domain transfers. For example, a CSP community may require each of its CSP members to nominate one or more of their respective nodes as gateway nodes, thereby reducing the number of possible gateway nodes from the total population of nodes in that community. These handful of gateway nodes can be equipped with special capabilities (e.g. trusted hardware [24]) to deal with the cross-domain transfer.

The gateway node in an origin contract-domain must use the published well-known peering point in the destination contract-domain to communicate its intent to commence a cross-domain transfer. The endpoint in the destination contract-domain may either handle the call itself (if it is equipped and authorized to do so), it could redirect the call to the relevant gateway-node in that domain. Figure 7 provides a high level illustration of some of the functions and capabilities needed for cross-domain asset transfers.

### 6.3 Identifiers for Contract Domains and VASP Numbers

Each autonomous systems (AS) in the Internet is allocated a globally unique AS-number. For example, in the United States this task is managed by the American Registry for Internet Numbers (ARIN) [50]. For the EU the organization is RIPE, for Africa it is AFRINIC, for Asia-Pacific it is APNIC and so on [51].

Today the VASP and virtual asset industry globally has yet to agree on a common VASP numbering scheme and customer identification scheme. The notion of a unique VASP number has been proposed in [52, 53], while other mechanisms have been contemplated, such as using the VASP’s Legal Entity Identifier (LEI) [54] within the VASP KYC-Certificate [55]. In the current work we assume that a contract-domain has a globally unique identifier that allows it to be distinguished easily from other contract-domains and VASPs.

When a customer of a CSP in a contract-domain invokes the asset transfer contract using a beneficiary address (public-key) or PayID address [56] that is not an entity (customer) in the same contract-domain, then an *address resolver* mechanism is needed to map from the beneficiary address to the contract-domain (blockchain network) where the beneficiary resides. This topic is discussed further in [49].

### 6.4 Asset Locking during Cross-Domain Transfers

A requirements for cross-domain asset transfers is preventing double-spend of the asset (inadvertently or otherwise) on the part of the customer who owns it. In this case, a double-spend would consist of a customer requesting a cross-domain transfer of their asset while at the same time using the same asset in a different transaction (e.g. locally in the same contract domain). In the current model, cross-domain transfers are performed by nodes belonging to CSPs in the
One approach to solve this dilemma is for the processing node (gateway node) to temporarily lock the asset while the transfer process is underway. The notion of “locking” is borrowed from the classic field of database transaction and concurrency-control [57, 44, 45]. In transactional database systems, locking techniques are used to “mark” a data item (e.g. database row) as undergoing an update by one process. Other processes are unable to access (write to) the data item until the lock is released.

Given the diversity of blockchain transaction processing models (e.g. UTXO in Bitcoin; external-owned accounts and smart contract accounts in Ethereum; etc.) we believe that (i) the contract-ledger is the only reliable shared-state and synchronization method for all the nodes in a blockchain network [58, 59], and therefore that (ii) the lock-state information for cross-domain transfers must be recorded on the contract-ledger so that the lock-state is visible to all nodes in the same contract-domain. From an audit and security perspective, the recording of lock/unlock information on the contract-ledger provides the benefit of historical traceability of cross-domain events in the case of disputes between CSP-communities.

The specific lock/unlock mechanism is dependent on the cross-domain atomic commitment protocol used by gateway nodes. However, in general they must perform the following tasks:

- **Asset locked transaction**: This transaction marks an asset associated with a customer public-key as being in a locked-state and therefore will not be processed by other nodes. A time duration may be set in the transaction header denoting the duration of validity of the lock, after which the lock automatically expires and the asset considered unlocked.

- **Asset unlock transaction**: This is an explicit unlock transaction that marks the asset as being “free” (unlocked state) on the ledger. An asset-unlock transaction must match an existing asset-lock transaction, and it is typically issued by the same entity (CSP node) that issued the lock. The purpose of an explicit unlock is to terminate a lock before the expiration of its timer. This feature is useful for cases such as an aborted cross-domain transaction (e.g. abort request from customer).

- **Asset lock-committed transaction**: This transaction marks a virtual asset as being henceforth permanently unavailable due to the asset exiting (transferred out of) the contract-domain. Typically, this transaction must refer to (include a hash of) a previous asset-locked transaction confirmed on the contract-ledger. It may include an identifier that points to the new home (destination contract-domain) of the virtual asset [1, 5].

Although the specific locking mechanism is beyond the current work, in general lock/unlock transactions must include at least the following parameters: the identifier of the asset being locked, the address (public key) of the current holder (customer), the timestamp value (or timer), and the hash of the confirmed transaction on the contract-ledger where the asset was last used. Similarly, an asset unlock transaction must include a hash of the earlier confirmed asset locked transaction.
6.5 Example of Flows in a Cross-Domain Transfer

An example of the flows that occur in a cross-domain transfer between two contract domains is shown in Figure 8. The gateway nodes are shown as G1 (owned by CSP-B) in domain CD1, and G2 (owned by CSP-X) in domain CD2 respectively. Alice is the originator, while Bob is the beneficiary. Since gateway G1 belongs to CSP-B, the CSP-B is the Originator-VASP. Similarly, CSP-X that owns G2 is the Beneficiary-VASP.

The transfer consists of four (4) general phases, including the commitment protocol embedded in the flows:

**Phase 1:** *Initiation of transaction and policy validation.* There are a number of pre-transfer tasks that need to occur in this phase:

- The processing node (gateway G1) must locate the correct destination contract domain CD2 where the beneficiary (Bob) is thought to reside.
- Gateway G1 must validate that gateway G2 is owned by a registered CSP (VASP), and vice versa.
- Gateway G1 must request gateway G2 to seek consent from the beneficiary (Bob) to receive the asset to be transferred. This protects the beneficiary and G2 (CSP-X) by giving them exculpatory evidence. An explicit consent from a beneficiary is a requirement in some jurisdictions (e.g. see FINMA [60]).
- Gateway G2 must validate that the virtual asset to be transferred from G1 is compatible with the core operating rules of the contract domain CD2.
- The gateway G2 must validate the legal status of this asset to its Asset Issuer/Acquirer. (In the previous Figure 7, this is shown as Line-2 from G1 to
G2, and Line-3 from G2 to its Asset Issuer/Acquirer).

- If all is well, gateway G2 transmits an acknowledgment to G1 that the transfer can proceed.

**Phase 2: Local locking of asset.** In this phase the gateway G1 issues a local asset-locked transaction on ledger L1 to the asset in question. This prevents double-spending on the part of the originator. Optionally, gateway G2 may indicate an incoming asset by issuing a candidate-lock on its ledger L2. The candidate-lock is not binding, but serves as an audit trail in case of disputes between the two CSP communities.

**Phase 3: Preparation to commit.** In this phase gateway G1 acting as the coordinator in the 2PC protocol \[44, 45\] signals readiness to commit to gateway G2.

**Phase 4: Finalization of commit.** In this phase the gateway G1 as coordinator signals to gateway G2 to perform the global commitment on ledger L2. Gateway G1 then issues an asset lock-committed transaction on ledger L1 to close its previous asset-locked transaction in Phase 2.

Gateway G2 records the new asset on its local ledger L2, assigning it to the public-key of the beneficiary Bob. If G2 employed a candidate-lock transaction on L2 previously in Phase 2, then G2 can also close that transaction with its own asset-locked transaction on ledger L2.

The astute reader may recognize that Phase 2 to Phase 4 constitutes a variant of the 2PC commitment protocol, often referred to as 3PC (i.e. three phase commit). In distributed databases this occurs through the use of a commit-prepare message followed by a global-commit message sent from the coordinator (node G1) to all recipient (in this case, node G2). The topic of reliability of commitment protocols have been extensively addressed in various literature over the past two decades (e.g. see \([57]\)).

### 7 The Contract Services Model: Design Principles

The contract service provider (CSP) model is based on the following design principles that takes into account code complexity considerations and the provider’s deployment considerations:

(a) **Contract simplicity principle**: Each smart contract should implement a simple and modular well-defined function, following classic object-oriented design principles. This is also referred to as the **decentralized primitives** principle.

(b) **Constrained authorship principle**: Each contract must be made available only by a contract service provider (CSP) entity within the group of CSPs.

(c) **Node diversity principle**: A contract service blockchain network must employ a diverse node-technology implementations and be owned/operated by a diverse set of providers.
(d) **Mediated oracle principle:** Any representation of value that originates from outside the contract service (contract domain) must enter (be introduced) into the contract service through the mediation of a contract service provider.

(e) **Opaque ledgers assumption:** Any cross-chain or cross-domain asset transfer protocol must be designed based on the assumption that the ledgers of the respective blockchains are not externally readable/writeable.

We discuss these design principles in the following.

### 7.1 Simple Primitives Principle

The goal of this principle is to re-orient the notion of DApps (decentralized applications) into the proper separation between primitive operations from complex business logic. Following the classic object-oriented design philosophy, complex applications are created using layers of modular objects, where each object implements rudimentary functions. This means that smart contracts must implement simple primitive functions that can be used (i.e. called) by higher layer applications, which may be complex and involve access to off-chain data sources. Such business applications should be implemented off-chain, with APIs providing access to the on-chain primitives.

This principle seeks to address the following challenges:

- **Cost of on-chain operations:** The use of contracts that implement simple primitive functions means that the number (cost) of on-chain operations is limited. This factor is an important consideration for CSPs who choose to use shared platforms (e.g. Ethereum) in implementing their nodes.

- **Interoperability at the protocol layer:** The use of simple primitives in one blockchain system provides the highest likelihood that semantically near-identical primitives are also used in other blockchain systems.

- **Privacy of business logic and data flows:** Many organizations in the financial sector and other industries have developed complex business applications that often embody business decision-making strategies. Some of these applications can be considered proprietary and some may access internal data-sources (e.g. private data stores in the organization).

By employing simple contract primitives that record shared state on the ledger but placing sensitive application-logic off-chain, organizations can retain their intellectual property while adding to the application’s integrations capabilities.

### 7.2 Constrained Authorship Principle

The goal of the constrained authorship principle is to address the quality and provenance issues with regards to smart contracts. In many permissionless blockchains today, the identity
of the author of a smart contract is unknown because the contract is bound only to a public-key.

Although the paradigm of permitting anyone to anonymously publish a contract on a blockchain platform (e.g. Ethereum) – as long as they pay the operations fees (i.e. gas) – may be beneficial for the platform owners, this paradigm is unrealistic from business organizations’ security and survivability. Most (all) medium to large Enterprise organizations have strict access policies with regards to the resources accessible to employees on the corporate network. Similarly, Internet access providers and ISPs maintain the availability and uptime of their network by strictly controlling access to the network elements (e.g. routers, switches, VPNs, etc). Demarcating the physical boundary of an ISP network (which is also a legal boundary) is therefore core to the business survivability of the ISP.

In practical terms, the constrained authorship principle means that for a given CSP community sharing a contract-ledger, only smart contracts (set of primitives) authored by a CSP member of the community is permitted to be published on the blockchain (i.e. on all the nodes and shared ledger). This has the advantage that contracts can be carefully designed, tested and implemented by CSPs within the contained environment of the contract domain.

This principle seeks to address the following challenges:

- *Demarcation of computational boundary, and business & legal responsibilities*: Similar to ISPs who need to demarcate their physical network boundary, contract service providers (CSP) need to demarcate their computational boundary as well as their business and legal liabilities. By limiting the origins and authorship of contracts to only CSP entities, the CSP-community members have a clear demarcation of their responsibilities to their customers.

  This is in radical contrast to the permissionless philosophy that leads to overall blockchain performance unpredictability and the need for users to verify every contract that the user wishes to call (i.e. verify manually or using formal verification tools).

- *Quality and safety of smart contracts*: Contract service providers are responsible for the functional quality and safety of their smart contract. This permits customers to make use the contract for the appropriate asset types, with assurance that the contract has been tested, analyzed and staged by the authoring CSP.

- *Code provenance and authorship identification*: Most (all) business applications have known authorship, and therefore known code provenance. In contrast, many smart contracts permissionless blockchains today are of unknown origin and is “posted” on the nodes of the blockchain using a public-key whose ownership is unidentifiable. These anonymous smart contracts are simply too risky for many legitimate businesses.

### 7.3 Node Diversity Principle

The Internet consists of a number of autonomous systems that together provide IP communications end-to-end from the sender to receiver. The diversity of ISPs and the networks that
form the Internet provide one of the key strengths of the Internet. A similar strategy is needed for contract domains, where CSP diversity and node-technology diversity \cite{18} provides the best strategy for survivability of the blockchain network as a whole.

Cyberattacks on blockchain networks can range from crude network-level denial attacks (i.e. DDOS attacks), to more sophisticated attacks based on the manipulation of consensus (e.g. in the case of anonymous nodes) and of smart contracts. Although theft of keys have occurred primarily on client endpoints (i.e. wallets), nodes (e.g. mining or forging nodes) which hold private-keys can also be a target of attacks.

This principle seeks to address the following challenges:

- **Node implementation diversity**: The uniform implementation of the node software stack in homogeneous platforms (e.g. Bitcoin, Ethereum) means that malware designed to target that specific software stack will affect all nodes in the network.

- **Service provider diversity**: Platforms that are directly or indirectly controlled (owned) by one or few dominating entities leads to poor levels of services overtime.

### 7.4 Mediated Oracle Principle

Smart contracts today are “blind” to data sources that are external to the platform that implement the smart contract. As such, developers of blockchain platforms have resorted to naming external data sources as *oracles* of truth – a reference to the Oracle of Delphi in Greek mythology. In practice, this means that any external data must be made present on the ledger in order for a smart contract to read and act upon it. Since the same copy of a smart contract is present on all nodes, this means that the invocation of any copy of the smart contract must read the same data item on the local copy of the ledger.

However, a key issue here is in deciding which external source of data is “trustworthy” to the user (caller) of the smart contract to begin with. This is one of the seemingly inherent contradictions of the “trustless” blockchain model: on one hand no single entity is trusted to execute the smart contract (hence the decentralized copies of the smart contract on each node); on the other hand, any meaningful use of smart contracts requires the importation of a digital representation of the real-world asset issued by a centralized “oracle” entity. It is this centralized entity that “binds” the digital representation to the real-world asset by cryptographically signing the assertion data-structure (e.g. signed JSON file, signed digital certificate, etc). The centralized entity stands behind its assertion (by signing it) and thereby takes on legal liability.

At the heart of the oracle problem is the inherent limitations of the smart contracts abstraction \cite{58, 59}. The abstraction is based on the classic object-oriented programming constructs of *methods* and *local data* (i.e. scoped variables), where a special *constructor* method instantiates (in memory) the methods (local functions) and the variables (local data) defined by the *class* of the object. When this programming abstraction is mapped onto a multi-node blockchain system – as is the case with Ethereum and Solidity \cite{11} – with a shared global state (i.e. blocks of the ledger) and shared code visibility (i.e. copy of smart contract
is on every node), the limitations of the method/scope-variable paradigm become readily apparent. Just as methods (local functions) in an object is limited in its visibility to data defined in its scope (i.e. data in its local memory), a smart contract is limited in its visibility to data found on the shared ledger. As far as a smart contract is concerned, anything not on the ledger does not exist.

The principle of mediated oracles seeks to address the practical limitations of the current form of oracles by ensuring that at least one CSP in a contract domain is verifying the truthfulness of the external oracle’s assertions (virtual assets) prior to introducing the virtual asset into the contract domain:

- **All oracle assertions pre-validated by CSP**: Any digital representations of assets asserted by an external oracle must be validated a CSP before the CSP introduces it into the contract domain shared by the CSP community. A customer of a CSP seeking to move their virtual assets into a contract domain must request its CSP to perform this importation.

  The CSP must (i) validate the source-authenticity of the virtual asset and its legal status, (ii) validate the expiration date of the virtual asset (if any), and (iii) obtain sufficient evidence that the virtual asset is not used in other blockchain systems.

- **All oracle assertions co-signed by CSP upon entry**: The CSP that validates the digital representations of assets (asserted by an external oracle) must also digitally sign the assertion when introducing it into the CSP community. This ensures liability lies with the CSP, and therefore deters the CSP from malicious behavior.

### 7.5 Opaque Ledgers Assumption

The structure of a contract service provider (CSP) community is based on the classic notion of a bounded IP network routing domain and observes two fundamental principles of the Internet architecture. These two principles are: (i) networks as bounded autonomous system (AS), and (ii) communications-context (meaning) as a higher layer function that exists at the edges end-to-end [3, 4]. These two principles represent pillars of the Internet architecture that has allowed the Internet to grow through the addition of independent autonomous networks where the interior of each network is opaque to the next network [1].

A key aspect of the autonomous system principle in the Internet architecture is that routing-data (e.g. interior route advertisements) belonging to an ISP is opaque (invisible) to other ISPs and external entities. This provides the freedom for an ISP to innovate within the confines of its own network (e.g. using new routing protocols and routers), while not impacting other ISPs. The ISP-to-ISP interaction occurs through the deployment of an exterior inter-domain routing protocol (e.g. BGPv4) that acts as a standardized interface between networks.

We believe a similar design assumption is needed for contract-domains and blockchain networks. We refer to this assumption as the opaque ledgers assumption, which states that any cross-chain or cross-domain asset transfer protocol must be designed based on the assumption
that the ledgers of the respective blockchains are not externally readable/writeable. A well-designed protocol that permits asset transfer across two blockchains with opaque ledgers will invariably work also for blockchains with non-opaque ledgers.

Note that the opaque ledgers assumption has implications on contract-level cross-chain conditionals, such as cross-chain hash-locks \[61\] and time-locks – which assume that the ledgers on both sides of the cross-chain transfer are readable/writeable (e.g. see \[62\] 46 \[63\] \[64\]). This means that for the CSP model and contract domains, any conditional-transfer constructs must be an artifact of the upper layer application that implements the business logic as mentioned earlier.

8 Conclusions

Today there is a great interest on the possible use of digital currencies as the national level, in the form of Central Bank Digital Currencies (CBDC) and fiat-backed Stablecoins. There are a number of possible strategies to implement CBDCs, including a non-blockchain approach following the classic Chaum design (e.g. GNU Taler).

Today the lack of interoperability among popular blockchain platforms and the rising cost of transactions on platforms employing the gas-fee model may discourage the use of blockchain-based solutions for CBDCs. As such, alternative models are needed that can retain the technological benefits of blockchain systems while using a different fee-for-service business model that does not rely on the tokenization of operations.

In this paper have proposed the Contract Service Provider (CSP) model as one such alternative.

References

[1] T. Hardjono, A. Lipton, and A. Pentland, “Towards an Interoperability Architecture Blockchain Autonomous Systems,” IEEE Transactions on Engineering Management, pp. 1–12, 2019, doi:10.1109/TEM.2019.2920154. [Online]. Available: https://arxiv.org/abs/1805.05934

[2] J. Martin, “Vitalik Proposes Solution to Embarrassing Lack of Bitcoin–Ethereum Bridge,” Cointelegraph, March 2020. [Online]. Available: https://cointelegraph.com/news/vitalik-proposes-solution-to-embarrassing-lack-of-bitcoinethereum-bridge

[3] D. Clark, “The Design Philosophy of the DARPA Internet Protocols,” ACM Computer Communication Review – Proc SIGCOMM 88, vol. 18, no. 4, pp. 106–114, August 1988.

[4] J. Saltzer, D. Reed, and D. Clark, “End-to-End Arguments in System Design,” ACM Transactions on Computer Systems, vol. 2, no. 4, pp. 277–288, November 1984.

[5] T. Hardjono and N. Smith, “Decentralized Trusted Computing Base for Blockchain Infrastructure Security,” Frontiers Journal - Special Issue on Finance, Money &
[6] V. Buterin, “Ethereum: A Next-Generation Cryptocurrency and Decentralized Application Platform,” Bitcoin Magazine, Report, January 2014, https://bitcoinmagazine.com/articles/ethereum-next-generation-cryptocurrency-decentralized-application-platform-1390528211/.

[7] Z. Voell and W. Foxley, “Decentralized Finance Frenzy Drives Ethereum Transaction Fees to All-Time Highs,” Cointdesk, August 2020. [Online]. Available: https://www.cointdesk.com/decentralized-finance-frenzy-drives-ethereum-transaction-fees-to-all-time-highs

[8] D. Cawrey, B. Keoun, and O. Godbole, “First Mover: Ethereum Faces Inflation Problem as Gas Fees Soar,” Cointdesk, August 2020. [Online]. Available: https://www.cointdesk.com/first-mover-ethereum-faces-inflation-problem-as-gas-fees-soar

[9] BBC News, “CryptoKitties craze slows down transactions on Ethereum,” BBC News, December 2017. [Online]. Available: https://www.bbc.com/news/technology-42237162

[10] P. Vigna, “CryptoKitties and Dice Games Fail to Lure Users to Dapps,” Wall Street Journal, May 2019. [Online]. Available: https://www.wsj.com/articles/cryptokitties-and-dice-games-fail-to-lure-users-to-dapps-11559122201

[11] C. Reitwiessner et al., “Solidity,” 2014. [Online]. Available: https://github.com/ethereum/solidity

[12] A. Shevchenko, “Using a DeFi protocol now costs more than $50 as Ethereum fees skyrocket,” Cointelegraph, September 2020. [Online]. Available: https://cointelegraph.com/news/using-a-defi-protocol-now-costs-more-than-50-as-ethereum-fees-skyrocket

[13] D. Siegel, “Understanding The DAO Attack,” Cointdesk, June 2016. [Online]. Available: https://www.cointdesk.com/understanding-dao-hack-journalists

[14] M. del Castillo, “Blockchain Hard Fork to Return DAO Funds,” Cointdesk, July 2016. [Online]. Available: https://www.cointdesk.com/ethereum-executes-blockchain-hard-fork-return-dao-investor-funds

[15] H. Chen, M. Pendleton, L. Njilla, and S. Xu, “A Survey on Ethereum Systems Security: Vulnerabilities, Attacks and Defenses,” August 2019. [Online]. Available: https://arxiv.org/abs/1908.04507

[16] FATF, “International Standards on Combating Money Laundering and the Financing of Terrorism and Proliferation,” Financial Action Task Force (FATF), FATF Revision of Recommendation 15, October 2018, available at: http://www.fatf-gafi.org/publications/fatfrecommendations/documents/fatf-recommendations.html.
[17] ——, “Guidance for a Risk-Based Approach to Virtual Assets and Virtual Asset Service Providers,” Financial Action Task Force (FATF), FATF Guidance, June 2019, available at: www.fatf-gafi.org/publications/fatfrecommendations/documents/Guidance-RBA-virtual-assets.html.

[18] D. Yaga, P. Mell, N. Roby, and K. Scarfone, “Blockchain Technology Overview,” National Institute of Standards and Technology Internal Report 8202, October 2018, https://doi.org/10.6028/NIST.IR.8202.

[19] Ethereum Foundation (EthHub), “Ethereum 2.0 Roadmap: Sharding,” accessed 1 September 2020. [Online]. Available: https://docs.ethhub.io/ethereum-roadmap/ethereum-2.0/sharding/

[20] S. Nakamoto, “Bitcoin: A Peer-to-Peer Electronic Cash System,” 2008. [Online]. Available: https://bitcoin.org/bitcoin.pdf

[21] Ethereum Foundation (EthHub), “Ethereum 2.0 Roadmap: Proof of Stake (PoS),” accessed 1 September 2020. [Online]. Available: https://docs.ethhub.io/ethereum-roadmap/ethereum-2.0/proof-of-stake/

[22] J. Khamar and H. Patel, “An Extensive Survey on Consensus Mechanisms for Blockchain Technology,” in Data Science and Intelligent Applications: Proceedings of ICDSIA 2020. Singapore: Springer Singapore, June 2020, pp. 363–374. [Online]. Available: https://doi.org/10.1007/978-981-15-4474-3_40

[23] W. Wang, D. T. Hoang, P. Hu, Z. Xiong, D. Niyato, P. Wang, Y. Wen, and D. I. Kim, “A Survey on Consensus Mechanisms and Mining Strategy Management in Blockchain Networks,” IEEE Access, vol. 7, pp. 22 328–22 370, 2019.

[24] T. Hardjono and N. Smith, “An Attestation Architecture for Blockchain Networks,” May 2020, available at https://arxiv.org/abs/2005.04293.

[25] P. Tasca and C. J. Tessone, “Taxonomy of Blockchain Technologies: Principles of Identification and Classification,” Ledger Journal, vol. 4, February 2019. [Online]. Available: 10.5195/ledger.2019.140

[26] T. Ankenbrand, D. Bieri, R. Cortivo, J. Hoehener, and T. Hardjono, “Proposal for a Comprehensive (Crypto) Asset Taxonomy,” in Proceedings of the 2020 Crypto Valley Conference on Blockchain Technology (CVCBT), June 2020. [Online]. Available: https://arxiv.org/abs/2007.11877

[27] MAS, “Project Ubin Phase 5: Enabling Broad Ecosystem Opportunities,” Monetary Authority of Singapore, MAS Report, July 2020. [Online]. Available: https://www.mas.gov.sg/-/media/MAS/ProjectUbin/Project-Ubin-Phase-5-Enabling-Broad-Ecosystem-Opportunities.pdf
[28] DTCC, “Project Whitney: Case Study,” Depository Trust & Clearing Corporation, DTCC Report, May 2020. [Online]. Available: https://perspectives.dtcc.com/articles/project-whitney

[29] ——, “Project Ion: Case Study,” Depository Trust & Clearing Corporation, DTCC Report, May 2020. [Online]. Available: https://perspectives.dtcc.com/articles/project-ion

[30] IBM, “Four-party credit/debit payment protocol (EU Patent EP1017030A2),” December 1999. [Online]. Available: https://patentimages.storage.googleapis.com/68/7d/68/51b6337757ed7a/EP1017030A2.pdf

[31] Visa, “Visa Core Rules and Visa Product and Service Rules,” Visa, Specification, October 2017.

[32] B. Lampson, M. Abadi, M. Burrows, and E. Wobber, “Authentication in distributed systems: Theory and practice,” ACM Trans. Comput. Syst., vol. 10, no. 4, p. 265?310, 1992. [Online]. Available: https://doi.org/10.1145/138873.138874

[33] T. Hardjono, “Federated Authorization over Access to Personal Data for Decentralized Identity Management,” IEEE Communications Standards Magazine – The Dawn of the Internet Identity Layer and the Role of Decentralized Identity, vol. 3, no. 4, December 2019. [Online]. Available: https://doi.org/10.1109/MCOMSTD.001.1900019

[34] B. Aboba, P. Calhoun, S. Glass, T. Hiller, P. McCann, H. Shiino, P. Walsh, G. Zorn, G. Dommety, C. Perkins, B. Patil, D. Mitton, S. Manning, M. Beadles, X. Chen, S. Sivalingham, A. Hameed, M. Munson, S. Jacobs, B. Lim, B. Hirschman, R. Hsu, H. Koo, M. Lipford, E. Campbell, Y. Xu, S. Baba, and E. Jaques, “Criteria for evaluating aaa protocols for network access,” November 2000, RFC2989. [Online]. Available: http://tools.ietf.org/rfc/rfc2989.txt

[35] R. Yavatkar, D. Pendarakis, and R. Guerin, “A framework for policy-based admission control,” January 2000, RFC2753. [Online]. Available: http://tools.ietf.org/rfc/rfc2753.txt

[36] J. G. Steiner, B. C. Neuman, and J. I. Schiller, “Kerberos: An authentication service for open network systems,” in Proceedings of the USENIX Winter Conference. Dallas, Texas, USA, January 1988. USENIX Association, 1988, pp. 191–202.

[37] J. Kohl and C. Neuman, “The kerberos network authentication service (v5),” September 1993, RFC1510. [Online]. Available: http://tools.ietf.org/rfc/rfc1510.txt

[38] J. H. Saltzer, “Protection and the Control of Information Sharing in MULTICS,” Communications of the ACM, vol. 17, no. 7, pp. 388–402, July 1974.
[39] D. E. Bell and L. J. LaPadula, “Secure Computer Systems: Mathematical Foundations,” The MITRE Corporation, Technical Report MTR-2547 I ESD-TR-73?278, (Vol. I-II), November 1973.

[40] D. F. Ferraiolo and D. R. Kuhn, “Role-Based Access Controls,” in Proc. 15th National Computer Security Conference, Baltimore, October 1992, pp. 554–563, https://csrc.nist.gov/CSRC/media/Publications/conference-paper/1992/10/13/role-based-access-controls/documents/ferraiolo-kuhn-92.pdf.

[41] Microsoft Corporation, “Microsoft Privilege Attribute Certificate Data Structure,” Microsoft Corporation, MS-PAC Specification v20140502, May 2014.

[42] P. De Filippi and A. Wright, Blockchain and the Law. Harvard University Press, April 2018.

[43] FATF, “12-Month Review of Revised FATF Standards on Virtual Assets and Virtual Asset Service Provider,” Financial Action Task Force (FATF), FATF Report, July 2020. [Online]. Available: http://www.fatf-gafi.org/publications/fatfrecommendations/documents/12-month-review-virtual-assets-vasps.html

[44] I. L. Traiger, J. Gray, C. A. Galtieri, and B. G. Lindsay, “Transactions and Consistency in Distributed Database Systems,” IBM Research Report, vol. RJ2555, 1979.

[45] J. Gray, “The Transaction Concept: Virtues and Limitations,” in Very Large Data Bases – Proceedings of the 7th International Conference, Cannes, France, September 1981, pp. 144–154.

[46] V. Zakhary, D. Agrawal, and A. E. Abbadi, “Atomic Commitment Across Blockchains,” June 2019. [Online]. Available: https://arxiv.org/pdf/1905.02847.pdf

[47] T. Haerder and A. Reuter, “Principles of Transaction-Oriented Database Recovery,” ACM Computing Surveys, vol. 15, no. 4, p. 287?317, December 1983. [Online]. Available: https://doi.org/10.1145/289.291

[48] M. Herlihy, B. Liskov, and L. Shriria, “Cross-chain Deals and Adversarial Commerce,” Proceedings of VLDB, vol. 13, no. 2, October 2019. [Online]. Available: https://doi.org/10.14778/3364324.3364326

[49] T. Hardjono, “Trust Infrastructures for Virtual Asset Service Providers,” August 2020, available at https://arxiv.org/abs/2008.05048.

[50] ARIN, “American Registry for Internet Numbers – Autonomous System Numbers (asn.txt),” 2018. [Online]. Available: https://www.arin.net

[51] Wikipedia, “Regional Internet Registry,” 2020. [Online]. Available: https://en.wikipedia.org/wiki/Regional_Internet_registry
[52] D. Riegelning, “OpenVASP: An Open Protocol to Implement FATF’s Travel Rule for Virtual Assets,” November 2019. [Online]. Available: https://www.openvasp.org/wp-content/uploads/2019/11/OpenVasp_Whitepaper.pdf

[53] InterVASP, “InterVASP Messaging Standards IVMS101,” Joint Working Group on interVASP Messaging Standards, Working Draft – Issue 1 – Draft G, March 2020.

[54] GLEIF, “LEI in KYC: A New Future for Legal Entity Identification,” Global Legal Entity Identifier Foundation (GLEIF), GLEIF Research Report ? A New Future for Legal Entity Identification, May 2018. [Online]. Available: https://www.gleif.org/en/lei-solutions/lei-in-kyc-a-new-future-for-legal-entity-identification

[55] D. Jevans, T. Hardjono, J. Vink, F. Steegmans, J. Jefferies, and A. Malhotra, “Travel Rule Information Sharing Architecture for Virtual Asset Service Providers,” TRISA, Version 7, June 2020. [Online]. Available: https://trisa.io/wp-content/uploads/2020/06/TRISAEnablingFATFTravelRuleWhitePaperV7.pdf

[56] A. Malhotra, A. King, D. Schwartz, and M. Zochowski, “PayID Protocol,” PayID.org, Technical Whitepaper v1.0, June 2020. [Online]. Available: https://payid.org/whitepaper.pdf

[57] P. Bernstein, V. Hadzilacos, and N. Goodman, Concurrency Control and Recovery in Database Systems. New York: Addison-Wesley, 1987.

[58] T. Dickerson, P. Gazzillo, M. Herlihy, and E. Koskinen, “Adding Concurrency to Smart Contracts,” in Proceedings of the ACM Symposium on Principles of Distributed Computing PODC’17. New York, NY, USA: Association for Computing Machinery, 2017, pp. 303–312. [Online]. Available: https://doi.org/10.1145/3087801.3087835

[59] M. Herlihy, “Blockchains From a Distributed Computing Perspective,” Communications of the ACM, vol. 62, no. 2, pp. 78–85, February 2019. [Online]. Available: https://doi.org/10.1145/3209623

[60] FINMA, “FINMA Guidance: Payments on the blockchain,” Swiss Financial Market Supervisory Authority (FINMA), FINMA Guidance Report, August 2019. [Online]. Available: https://www.finma.ch/en/~/media/fnma/dokumente/dokumentencenter/myfinma/4dokumentation/fnma-aufsichtsmitteilungen/20190826-fnma-aufsichtsmitteilung-02-2019.pdf

[61] T. Nolan, “Alt chains and atomic transfers,” May 2013. [Online]. Available: https://bitcointalk.org/index.php?topic=193281.msg2224949#msg2224949

[62] P. Ezhilchelvan, A. Aldweesh, and A. van Moorsel, “Non-blocking two phase commit using blockchain,” in Proceedings of the 1st Workshop on Cryptocurrencies and Blockchains for Distributed Systems (CryBlock’18). New York, NY, USA:
[63] M. Herlihy, “Atomic Cross-chain Swaps,” in *Proceedings of the ACM Symposium on Principles of Distributed Computing PODC’18*. New York, NY, USA: Association for Computing Machinery, July 2018, pp. 245–254. [Online]. Available: https://dl.acm.org/doi/pdf/10.1145/3212734.3212736

[64] E. Heilman, S. Lipmann, and S. Goldberg, “The Arwen Trading Protocols (Full-Version).” [Online]. Available: https://eprint.iacr.org/2020/024.pdf