Towards Blockchain-enabled Open Architectures for Scalable Digital Asset Platforms

DENIS AVRILIONIS, Compellio SA, Luxembourg. denis@compell.io
THOMAS HARDJONO, MIT Connection Science & Engineering, USA. hardjono@mit.edu

Today there is considerable interest in deploying blockchains and decentralized ledger technology as a means to address the deficiencies of current financial and digital asset infrastructures. The focal point of attention in many projects on digital asset and cryptocurrency is centered around blockchain systems and smart contracts. Many projects seek to make the blockchain as the centerpiece of the new decentralized world of finance. However, several roadblocks and challenges currently face this predominant blockchain-centric view. In this paper we argue that the proper and correct perspective on decentralized economy should be one that is asset-centric, where the goal should be the consistent lifecycle management of assets in the real-world with their digital representation on the blockchain. We introduce the notion of the digital twin to capture the relationship between a real-world asset and its on-chain representation. A digital twin container is utilized to permit off-chain state persistence and on-chain state traceability, where the container can be deployed on the blockchain as well as on traditional application servers. The digital twin container becomes the bridge between legacy infrastructures and the newly emergent blockchain infrastructures, permitting legacy systems to interoperate consistently with blockchain systems. We believe this asset-centric view to be the correct evolutionary direction for the nascent field of blockchains and decentralized ledger technology.

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1 INTRODUCTION

The emergence of blockchains and smart contracts technology to enable the tokenization of financial assets has propelled great interest in smart contracts as a potential paradigm for decentralized finance. Like the various financial networks that today exist in different trading blocks, we believe that multiple blockchain networks will emerge in the future and that different forms of tokenized assets will also be deployed. This raises several challenges with regards to the proper place of blockchain and distributed ledger technology (DLT) within the landscape of financial computing generally and within open architecture more specifically. A key challenge in achieving open and accessible platforms as part of the vision of decentralized finance is that of the integration of blockchain and DLTs with legacy systems and infrastructures.

For digital assets to freely flow among such heterogeneous systems we must ensure that the overall computation paradigm for a conceptual “network of networks” offers openness and trust. In particular, the ability to maintain the consistency of the state of assets is a key capability requirement of all systems participating in such a globally interconnected world.

The current design of blockchain and smart contracts indirectly leads to the creation of silos, both data and assets. This is because, among others, the current smart contracts paradigm has a very constrained view of the world and requires particular components (known as "oracles") to interact with other external systems. These oracles have to "pull in" data from the external world and make it available on the ledger of the blockchain.

We believe that a new and broader computational paradigm is needed to underpin and encompass blockchain-based digital asset transactions. This new paradigm must permit assets
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to flow into and out of blockchains and legacy systems seamlessly. The new paradigm must also allow off-chain data and other asset-related state information in digital form to be reachable by the smart contract. Moreover, computations occurring in legacy systems must also be possible in coordination with smart contracts.

This implies that good design principles are needed for the following: (a) to minimize on-chain state information, (b) to connect/link on-chain state to richer off-chain information (maintained by an asset state "custodian" entity), and (c) to employ an active function/entity that coordinates the exchange of assets among heterogeneous systems.

When an application program (e.g., an asset trading application) seeks to modify the state of an asset, it needs to ensure that the real-world asset (e.g., real estate ownership certificate) and the digital representation of the asset on the blockchain (e.g., materialised by smart contract code) are synchronized. To address this challenge and central to our approach, is the ability of a system – either blockchain-based or non-blockchain based – to mirror the state of real-world assets (both digital or physical assets) with their digital “twin” representations. This continuous synchronization is performed to prevent changes in the asset ownership on the blockchain from being conducted without a corresponding state-change in the real world asset.

To ensure the correct and consistent state on both worlds, we introduce the notion of the asset digital twin and a corresponding mediating software layer – which we refer to as the digital twin container (see Section 5) – sits in between the two worlds (on-chain and off-chain).

To achieve this new paradigm, we also need to enhance current architectures to include functions related to: (i) the management of the asset repository (off-chain) and (ii) related to the verification of the consistency of on-chain state information (which we refer to as state verification henceforth).

Related to maintaining the consistency between on-chain/off-chain states, we borrow the classic database notion of the Logical Unit of Work (LUW) to mean the set of sub-transactions that must complete across various other computers in order to complete the work. The LUW corresponds to the traditional attribute of a transaction in a distributed database system that must satisfy the ACID properties (Atomicity, Consistency, Isolation, Durability). The LUW is a way to unify the mixed world of on-chain and off-chain state management, where a single top-level transaction may in fact be composed of a spread of sub-transactions [1] that may span across multiple computers systems. Here, each sub-transaction can be either off-chain or on-chain, and each must reach final a commitment stage in order for the parent top-level transaction to be considered as committed or settled.

In order to combine off-chain persistence of state information and the on-chain timestamping effect of the blockchain upon the digital twin (i.e., the on-chain digital representation of the asset), we introduce the approach of the Digital Twin Container (DT-Container). A given DT-Container can be deployed on a blockchain or within a traditional application server, and it can host computational units either as smart contracts in the former case, or as software packages in the latter case. By following the classic and proven Design by Contract approach [2] the DT-Container checks for pre-/post-conditions and invariants before and after processing the state of digital twins. Invalid properties may lead to non-execution of the code or to the invalidation of the computation results. This is in order always to maintain consistency of the state of digital twins with respect to the corresponding assets in the real world.

By using this approach, the computation that modifies the state of assets can be performed not only by smart contracts but also by other applications running in non-blockchain systems (including legacy systems). Besides the usual construct / read / update / destruct operations, the DT-Container is also responsible for negotiating and executing the transfer of assets to and
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from other external systems via a fully transactional digital twin, thus enabling free-flow of assets in a consistent manner in the context of global LUWs.

With regards to digital assets, today there is tremendous interest in digitizing assets and making these assets accessible and tradeable via decentralized systems, such as blockchains and DLT networks. Adding to this mix – and often introducing confusion – is the fact that some blockchain systems possess the technical capability to generate and manage endogenous tokens (e.g., ERC-20 compliant tokens on Ethereum [3]) that may be considered a new class of assets.

In the current work we seek to bridge the world of off-chain assets with technical capabilities that are available on-chain. As such, we distinguish among the following types of assets:

(a) Legally recognized assets in non-digital representation (off-chain): These are assets that exist off-chain, usually represented by depository receipts of certificates.

(b) Digitized equivalents of legally recognized assets (off-chain): These are the local digitized versions of (a) above where, for example, a depository receipt (paper) has been digitally represented in the local database (or local ledger) of the depository institution (e.g., see [4, 5]).

(c) On-chain tokenized assets: This includes exogenous digitized assets (e.g, (b) above) that have been tokenized, as well as ledger-endogenous digitized assets.

In our approach, Digital Twins are digital representations of assets, be they off-chain digitized assets (case of (b) above) or, native on-chain assets (case of (c) above).

The topic of digital assets, tokens, and their definition are out-of-scope for the current work, and has been treated elsewhere (e.g. see [6, 7] for a discussion on the economic impact of tokenized assets, see [8] regarding NFTs and see [9–11] for industry efforts to standardize the definitions of tokens and related assets).

2 LIMITATIONS OF THE CURRENT SMART CONTRACT PARADIGM

An important core idea underlying the notion of smart contracts today is the sharing of common functions and state information (data) on the ledger. Both of these computing constructs are not new inventions but rather originate from the field of object-oriented programming (e.g., Smalltalk, C++, Java). Indeed, the work of [12] immediately refers these constructs as objects in the classical object-oriented programming sense, where the function is typically referred to a methods and the state as variables in the object.

The innovation introduced by smart contracts as exemplified by the Ethereum platform [13] is the replication of the function/state modules across all nodes of the blockchain platform and the tight coupling with the ledger as the mechanism to store the output of the smart contract [14]. This means that the smart contract code and its resulting output are readable by any other smart contract on the same platform.

The author of a smart contract can design the logic of the contract object to be such that when a piece state-data (such as a digital asset representation) is being used (accessed) by one node (e.g., instance X in node Y at location Z) that the node has exclusive use of it, by virtue of the consensus mechanism being utilized by the nodes (e.g., proof of stake). Once the object instance at the node terminates execution and produces changes to the state-data, that new state-data is appended to the ledger (i.e., new block propagated to all nodes). Given the same input data, any copy of the smart contract (i.e., on any node) must produce the same output.

The smart contract code today has a limited world-view because unlike other types of software it cannot rely on information fetched from sources outside the ledger – which may be ever-changing
Fig. 1. Illustration of the tight coupling between smart contracts and state/data recorded on the replicated nodes of the blockchain

(ephemeral) or become unavailable very soon after. This means that some time \( t \) later other peer nodes may not have access to the identical data from the external source, and therefore will be unable to validate the veracity of the information.

Due to the above limitations, special components – referred to as Oracles – are needed to make these externally-sourced data available on the ledger by writing these data onto the blocks of the ledger.\(^1\) However, this implies that an increasing amount of data must be added to the ledger of the blockchain so that smart contracts can read this data (see Figure 1). Over time, this leads to the accumulation of data on the ledger, potentially leading the ledger becoming a silo of data over time.

3 THE ORACLE PROBLEM REVISITED

Blockchains have been designed with the fundamental assumption that the state of the overall system is defined by the combination of: (a) the content of wallets (i.e., digital tokens bound to public keys), and (b) the state of smart contracts interpreted by the system. This closed view often leads to the distinction between on-chain state (the state of the blockchain ledger system) and off-chain state (the state of the outside world). Besides technical aspects related to synchronizing non-blockchain systems with on-chain digital assets state, several issues are hindering the road to blockchain-based digitization/tokenization [15]. These include the absence of the legal framework and regulations to confer legal value to on-chain records, the lack of legal accountability for those records in the context of data privacy [16] and corporate confidentiality protection. In reality – and against the blockchain fundamental design assumption regarding wallet state and smart contract state – the off-chain data and information will continue to play an important role in asset-related transactions, and thus the management of such information should be considered as a significant component of future blockchain-enabled business solutions.

Due to the intrinsic closed design of blockchain systems, when building business applications beyond crypto-tokens (e.g., tokenized currencies), it is common to federate actors from a given industry to (re)build processes and digital assets models around dedicated purpose-built blockchain

\(^1\)It is worth noting that Oracles themselves can implement simple smart contracts to make external data available to other “computational” (non-oracle) smart contracts in the same blockchain system.
systems. Such systems run as stand-alone private or consortium networks, thus creating several silos of information even within the same industry segment and for the same purpose [17]. The challenge of the integration of legacy systems with blockchains is an open hot topic and the use of Oracles plays a fundamental role in that context [18].

As stated in [19], the various problems with the current architecture of blockchains emerge whenever there is the need for interactions with the world outside the blockchain system. In such cases, trust must be delegated to Oracles, which are located outside smart contracts\(^2\). Several approaches in implementing Oracles for blockchain-based systems have been identified in the literature [20].

Viewing the problem not from a smart contract point of view but from a digital asset perspective, we can say that the blockchain computational model is based on code executed by the platform to manage and maintain the state of endogenous digital assets (i.e., assets created from within the platform). If we revisit the definition of the Oracle problem in that sense, we can state the following:

Blockchain computation works as a siloed system. Smart contracts deployed on a blockchain system can only cover computation related to the management of endogenous digital assets within that (blockchain) system. They cannot adequately address business cases involving interaction with other systems or management of digital assets that can freely flow across systems other than that specific blockchain system.

4 OUR APPROACH: AN ASSET-CENTRIC MODEL

To solve the apparent conflict between the current smart contract paradigm (claiming to be a decentralized and independent compute unit) and the fact that smart contracts depend on Oracles, we propose a twofold approach:

- To consider smart contracts as stateless processing units (like stored procedures in traditional Relational Data Base Systems - RDBMS) that perform the manipulation of the stateful digital twin objects. Such smart contracts are executed within a Digital Twin Container (DT-Container). During a transaction cycle, the smart contracts request access to the digital twins via the DT-Container. The DT-Container serves copies by-value of the digital twins to the smart contracts. The smart contracts modify the state of the received digital twins, and then at the end of processing, they return the modified digital twins to the DT-Container for an update. The smart contracts cannot duplicate any state of the digital twins nor perform any side-effect computation affecting the state of the digital twins.

- To use the notion of the “Design by Contract Specifications” (DbCS)\(^3\) which was developed by Bertrand Meyer in the early days of Object-Oriented Programming [21]. The basic concept of the DbCS is that the caller of the object-code and the provider of the object-code must come to an agreement regarding the specification of the inputs, outputs and the side-effects of invoking the object-code. In simple language, there needs to be a binding agreement (aka “contract”) between the caller/invoker of the object-code and the object’s code itself (i.e. as defined by its authors). In our approach, each time a DT-Container

\(^2\)We should restate here that the Oracle problem affects only the cases where smart contracts of a blockchain system are required to make decisions based on external sources (e.g. stock index, sensors, information managed by external IT systems, state of exogenous physical or digital assets etc.). Cases like Bitcoin, where the state of the system is entirely endogenous, can work without any of the problems addressed here.

\(^3\)To avoid confusion in the terminology where the word “smart contract” is used, here we use our long phrase “Design by Contract Specification” (DbCS) instead of Meyer’s original phrase “Design by Contract”, although the intent is clear.
receives an updated digital twin, it verifies whether pre/post conditions and invariants are verified and if so, it proceeds to persistently modify the digital twin state.

As a result of the above approach, smart contracts can be seen as objects solely implementing behavioral patterns in the sense of the GoF Design Patterns [22] vocabulary (see [23] for a short description of the “Gang of Four” (GoF)). Structural aspects of the design of a system are primarily managed at the level of the DT-Container component, handling the lifecycle of the digital twins.

We believe that the positive benefits of the smart contracts paradigm can be realized without the danger of the siloed data only when the focus is correctly placed on the assets. That is, we need to view the problem from an asset perspective and design the architecture for smart contracts and blockchains to fulfill the requirements of the assets lifecycle. These requirements include ease of moveability (migration) of assets across new blockchain/DLT systems and legacy systems with the use of digital twins, and the privacy of state information associated with digital twins (and their correlated assets).

There are several considerations and assumptions for the design of an Asset-Centric scalable system:

- **Correlation of assets with digital twins**: The digital twins are mirroring real-world (digital or physical) assets. The digital twins are manipulated either by smart contracts or traditional software services. During their lifecycle, the digital twins maintain the strict correlation with the underlying assets.

- **Persistent state of digital twins**: There must be some means to persist the state of a digital twin that may combine on-chain and off-chain state information. Thus, for example, a digitized bearer bond exists both outside the blockchain (e.g., in printed sheets with serial numbers in traditional repositories such as the DTCC [4]), while its ownership-state is recorded on the blockchain via its correlated digital twin. Programmatically, the state is defined by a tuple of (typed) variables.

- **Consistent syntax for smart contracts expression**: Independent of how a smart contract is implemented, the syntax for the expression of transition between states of the digital twin must be defined in terms of pre/post-conditions and invariants expressed as type/value constraints on the digital twin variables.

- **Unambiguous declarative definition of assets**: The description of the Digital twin – in terms of variables and states – can be done in a declarative way.

The main novelty in our approach is that we move the central architectural focus from the application logic (implemented either in traditional application services or in smart contracts) to the DT-Container that maintains the digital twins. Rather than considering application logic as the core, we instead consider that the application logic is unreliable, untrusted, and even potentially written with malicious intent.

Here, we introduce two important computing constructs that aim to maintain the consistency of the assets between the off-chain world and the on-chain state digital twin representation. The first construct is the blockchain DT-Container that interfaces between the on-chain and off-chain states of the asset. The second construct is the Logical Unit of Work (LUW), which views the processing upon assets to consists of many steps (possibly across multiple blockchains) but which must be completed as an atomic unit. The consistency of the applications is based on the state of the digital twins – which can only be updated by their DT-Container if and only if their DbCS is verifiable at any moment during their lifecycle. The DT-Container guarantees that modifications – including the transfer of the digital twins across systems – are performed in a controlled way.
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Fig. 2. Illustration of the various kind of containers emerged over the last decades

based on a decentralized Logical Unit of Work (LUW) protocol. All participants in such a LUW, including Applications and DT-Containers are collaborating by consistently modifying digital twins using a 2 phase-commit approach [24]. The various concepts introduced here are illustrated in the following sections.

5 ASSET-CENTRIC ARCHITECTURES

5.1 Gateways

The concept of gateways between blockchain systems proposed in [1], and recently utilized by the Open Data Assets Protocol (ODAP) [25, 26] seeks to address the lack of interoperability between blockchain systems. Following the ODAP design, here a Gateway is a component that negotiates transfer of Digital Assets to and from a given blockchain system by collaborating with the Gateway of a remote blockchain system based on a set of primitives defined by the protocol (e.g., the ODAP protocol). Gateways are responsible for the complete cycle of lock–transfer–commit of digital assets among blockchains.

However, we believe that for the notion of asset transfers to reflect a consistent correspondence between the digital asset (as represented by ledger-state on the blockchain) and the real-world asset as recorded in the off-chain repository (e.g., DTCC [4]), the design of gateways needs to be extended as described in the following sections. This extended component implemented in the form of the DT-Container, not only covers exchanges among systems (blockchain or otherwise), but it also manages consistency between the digital twins, their correlated assets, and the processing of their lifecycle by applications (smart contracts or traditional software packages).

5.2 Expanding the Role of Gateways: Digital Twin (DT) Containers

The notion of a container is not new and has been used in different contexts in the last few decades. In the early 2000s, containers were used to refer to application-level coding frameworks, which typically package technical capabilities such as remote invocation, concurrency, load balancing, transactionality, authentication, etc. Examples of such containers include the Enterprise Java Beans (EJB) Containers – which provides a run-time environment for enterprise beans within the application server [27] – and the Web Container and “Application Server” containers in general
(see Figure 2). During the 2010s, the containers were also used to refer to virtualization capabilities at the level of the operating system (e.g., hypervisors), while more recently the containerization concept has expanded to deployment capabilities (e.g., Docker, Kubernetes).

In our case, the notion of Digital Twin Container is instead a cross-platform software framework that, when deployed on a target system would offer the same set of technical capabilities regardless whether the underlying system is a blockchain/DLT or a traditional application server software stack.

In our definition, the Digital Twin Containers must possess the following features or aspects:

- **Clear separation between digital twins and assets**: Since assets can be in digital or physical form, it is therefore essential to make a clear distinction between the asset themselves and their correlated digital twins. Digital twins are purely in digital form and are modified by applications (smart contracts or traditional software packages). Assets – which may be in non-digital form or in digital representation locally – are managed by specific entities that run specialized software components (referred to as Asset Providers below). The legal entities that define and issue assets must bear full accountability regarding the various aspects of issuance and management of the assets.

- **Commitment at the level of Logical Unit of Work**: Instead of focusing on the unit of transfer as the asset itself (e.g., transferring tokens), the commitment protocol must be applied to the LUW in its entirety. That is when a gateway accepts the engagement to transfer an asset across blockchain networks, the gateway is agreeing to provide resources to complete the entire LUW that encompasses both the digital twin and the correlated asset. Furthermore, the desirable ACID properties (atomicity, consistency, isolation, and durability) [28] are also desirable for current blockchain-based transactions.

- **DT-Containers as coordinating transaction managers**: A further implication of the LUW as the unit of commitment between two DT-Containers is the role of the DT-Container as transaction manager in the sense of the classic component handling distributed transaction processing [29].

- **Out-of-band applications interactions**: The shift of focus to an asset-centric view implies that user interactions occur between applications (i.e., service end-points or APIs) operated by the users. The application-to-application interactions occur outside and before any actions of the blockchain level.

### 5.3 DT-Container components

As shown in Figure 3, a DT-Container implements technical requirements related to managing the lifecycle of digital twins, including the exchange of assets across heterogeneous systems. DT-Containers can be deployed directly into a DLT. In such case the DT-Container is a set of smart contracts that are executed directly by the virtual machine of the DLT. In other terms, the DT-Container is a smart contract framework that coordinates execution of other “business-service level” smart contracts. Saying this, it is also possible to implement a DT-Container on a traditional application server, and thus being able to manage digital twins on a non-DLT system. In such case the DT-Container would be a framework implemented using traditional software (e.g. Java/EJB), with assets being managed, for example, in a traditional RDBMS. The interaction protocol among DT-Containers would hide the internal technological stack and would allow a seamless flow of interaction among DLT and non-DLT systems. Irrespective of the technological stack that is used to implement a DT-Container, it should always be possible to maintain trace of DT-Container's
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Fig. 3. Overview of the placement of core business logic away from the smart contracts layer and the validation of outputs of the logic using a DT-Container

In the specific case of a DLT stack, developers can integrate a DT-Container in the design of enterprise DLT applications in the following manner:

- They can deploy stateless smart contracts in a smart contract orchestrator. The smart orchestrator coordinates the execution of the smart contract in accordance with the architecture of the underlying virtual machine. It offers a framework for the deployed smart contracts to retrieve digital twins while confirming any authentication policies related to accessing and modifying the state of digital twins (and their correlated assets). The smart contract orchestrator is also responsible for the consistency of modifications of digital twins in the context of LUWs.

- They can implement interaction of applications with Repositories to manage the lifecycle of digital twins. The Repository components handle the basic Construct/Read/Update/Destruct (CRUD) operations for digital twins. The digital twins are defined in a declarative manner as state objects with state-transition logic, including DbCS governing the transition of states and invariants. A digital twin verifier of the DbCS is responsible for the global consistency for every state transition of the digital twin requested by a smart contract.

- They can integrate with identity providers via the Identity Provisioning module to obtain authentication credentials: The Identity Provisioning module implements standardized interfaces with Identity Providers that are able to authenticate users (e.g., via standard authentication and authorization protocols, such as Kerberos [30], OpenID-Connect [31], SAML2.0-SSO [32] and newer schemes such as DID methods [33]). This permits the verification of whether modifications of digital twin states have occurred according to
policies declared in the definition of the state transition of digital twins (e.g., must be performed only by authenticated and authorized entities).

- They can benefit from *Asset Providers* that are connected to the DT-Container via Repositories and which manage real-world assets (physical or digitized): Asset Providers are software components that act as “custodian” of assets. The legal entity that runs an Asset Provider component bears the legal responsibility for issuing and managing assets. In terms of technical constraints Asset Providers are required to implement ACID transactions for assets (eventually by escrowing assets for the duration of LUWs). That way, they can ensure the correct correlation of their assets with the corresponding digital twins that participate in LUWs.

6 DT-CONTAINER MEDIATED ACCESS

One of the key roles for DT-Containers is to mediate between independent systems/networks and to hide the complexity of the internal systems from outside entities. In the context of our asset-centric model for smart contracts and blockchains, we believe that DT-Containers provide a suitable means to achieve the desirable goals stated in the previous section. When a DT-Container is deployed in a blockchain system, it ensures that a consistent state is achieved before and after the target smart contract on the blockchain is invoked. That is, the DT-Container must ensure that there is agreement and synchronization between the behaviors of on-chain smart contracts and the inputs, outputs, and side-effects of the underlying assets.

More specifically, DT-Containers must satisfy the following:

(1) Must provide full synchronization of digital twins and real-world assets: In order to do so, it must be possible for applications to verify that assets are reserved and can be committed upon successful completion of an LUW. Digital twins should be fully correlated with their assets during their whole lifecycle. Direct verification (for example through API calls to asset providers) should be possible at any time by applications, and it can be decisive to commit or roll-back an LUW.

(2) Must allow asset verification for local as well as for remote systems: Although the blockchain can guarantee the persistence of state data on the ledger replicated by all its nodes, applications may not have access to the state of digital twins and underlying assets. DT-Containers provide mediation of access to asset state whether such assets are managed in the local system or in a remote system. In the latter case, communication among DT-Containers would facilitate access to the state of digital twins and assets participating in the same LUW.

(3) Must provide the interface for off-chain systems to invoke on-chain smart contracts: Another mediating role of a DT-Container is to provide an interface for off-chains (non-blockchain) systems to invoke specific types of smart contracts indirectly. This may be an important function for use-cases of private/permissioned blockchains. In these cases, the DT-Container validates authorship and code-safety and can invoke the smart contract on behalf of external systems.

In summary, DT-Containers coordinate their actions to implement decentralized transactions in each participating system (blockchain or legacy). Successful completion of the LUW is achieved when all individual transactions in each system are completed in a successful manner. Otherwise, all operations are rolled-back, and all digital twins participating in the LUW are reverted to their original state at the beginning of the LUW.
7 ARCHITECTURAL IMPLICATIONS

7.1 Implications for smart contract virtual machine design

In the approach adopted by programmable blockchain systems so far, smart contracts are the central component of the design. The Oracles act as auxiliary components supplying smart contracts with information from the external world. In our approach, the Digital Twins and related Repositories play the main role by guaranteeing that Digital Twins and their correlated Digital Assets managed by AssetProviders are consistent at any point in time.

In our case the smart contracts are processing units that obtain Digital Twins from Repositories, perform actions with the intent of updating the state of these Digital Twins, then request for update of the state. Repositories are strictly managing updates of the state of Digital Twins.

Smart contracts are effectively stateless process units. In the case the DT-Container is deployed on a DLT system, the DT-Container and the SmartContractOrchestrator (see Figure 3) are themselves smart contracts that act as frameworks that implement patterns to coordinate interactions among smart contracts deployed by developers. Much like Enterprise Java Beans (EJBs) deployed in an EJB container, smart contracts deployed by developers run inside the SmartContractOrchestrator. All interactions with Repositories, Digital Twins, as well as exchanges with applications from remote systems go through the DT-Container layer.

7.2 Implication for cloud service development

The notion of application server container is quite common in traditional web applications. Beyond traditional services like transactions management systems or user identification management, DT-Containers for non-blockchain SaaS systems (Software-as-a-Service) allow for the implementation of a standard mechanism to communicate with DT-Containers in remote blockchain systems and vice-versa. The inter-DT-Container interactions must be standardized in order to permit Logical Units of Work (LUWs) to spawn across these systems (i.e., across traditional legacy systems and blockchain-bases systems).

7.3 Implication for Asset Providers

Asset providers must implement ACID behavior in the management of their Assets. In that sense, the asset providers are resource managers with the responsibility to make assets available to applications via DT-Containers. Asset Providers can range from databases or Enterprise resource planning (ERP) systems, to smart contracts delivering on-chain digital assets (e.g., Ethereum ERC-20 or ERC-721 smart contracts). It is the responsibility of the Asset Provider to comply with the interaction pattern defined by the DT-Container to maintain the correlation between Digital Twins and Assets during computations in the context of Logical Units of Work (LUWs). Repositories are interacting with Asset Providers to commit or roll-back resources based on the status of the LUW.

7.4 Centralization vs decentralization

Decentralization introduces absence of central control in the technical architecture of systems. However, a clear distinction must be made between accountability and liability (which are centralized by essence) and the decentralized software architectures.

For use cases that involve legal entities or public institutions it is unlikely that responsibility and accountability will be delegated to programmers of smart contracts or software applications without strict control in terms of the legal implications related to offering assets to users. The issuance of assets is by definition centralized. Even in the case of the Decentralized Autonomous Organization (DAO) project contention [34] (the resolution of which resulted in the fork within
the Ethereum blockchain [35]), the decision to carry-out the fork was in reality made by a small
group of people in a centralized manner.

The DT-Container is not thus a component that defies the decentralization principle of
blockchain. Instead, it makes explicit the basic fact that digital assets must be managed under clear
responsibility by well-identified parties.

8 A NOTE ON ASSET AND OWNER IDENTIFICATION

With the rise of blockchain technology, cryptocurrencies and the use of public-keys as a means to
transact on the blockchain, there has been considerable confusion in the industry regarding the
matter of digital identity [36]. Among others, some confusion exists relating to (a) the authority to
designate (assign or allocate) namespace ownership and the identifiers within the namespace, (b)
the day-to-day control over the namespace (and any identifiers within it), and (c) the authority to
bind a public-key to an identifier under a given namespace.

The source of authority in binding a public-key to an identifier (e.g., subject’s name) is
crucial in digital transactions using the public-key (both on-chain and off-chain). Parties in a
bilateral transaction typically wish to obtain assurance that they are dealing with the correct entity
(possessing the correct public-key) in the transaction. They wish to reduce risk, and therefore require
that risk to be allocated to (assigned to) the entity that performs the binding of the public-key to the
identifier. This role as the binding authority has traditionally been performed by the Certification
Authority (CA) entities, who typically operate under a contractual service level agreement (SLA)
referred to in the industry as the Certificate Practices Statement (CPS) [37]. The rudimentary CPS
is defined in [38] for X.509 certificates.

In the context of digital twins, each digital asset (non-human asset) must be assigned a
globally unique identifier string (under a unique namespace) by a naming authority. For example,
for certain categories of financial assets, an International Securities Identification Number (ISIN)
consisting of a 12-digit alphanumeric code must be assigned to the asset. The agency within each
country with authority over its ISIN namespace is the country’s respective National Numbering
Agency (NNA). This single source of naming authority has the benefit that there is perpetual
consistency between: (i) the digital asset in the cyberworld (recognized via its digital identifier,
such as the ISIN number), and (ii) the real-world asset that may be physically located in a certain
part of the world (e.g. paper certificates of ownership in repositories, such as in the DTCC in New
York).

Recently, with the emergence of blockchains and DLT systems, the notion of a "self-sovereign"
identity [39] has come to the forefront as a means for individuals to obtain control over their digital
identities. This desire is not new, and it is as old as the Internet itself. The core concept in SSI is
that a permissionless blockchain system would permit an individual to declare ownership of a
given public-key pair by way of "publishing" – to the decentralized ledger of the blockchain – a
binding between the public-key under the control of the individual and the name-string of the
individual. Here, publishing is taken to mean that the matching private-key would be used to sign
the blockchain transaction, thereby providing to the community a proof-of-possession (PoP) of the
private-key. Since the ledger is replicated at all nodes, unauthorized modifications to the binding
would be infeasible. Furthermore, "self-sovereignty" is thought to have been achieved because the
individual becomes the sole entity who can (at any time) update the ledger of the blockchain with
newer bindings. Data structures to represent this binding have been developed [33].

We believe the SSI approach – like the PGP approach [40] of the 1990s – confuses the basic
notions of (a) control over a public-key pair and (b) the accountability and responsibility of utilizing
the key pair. The decentralized ledger may provide an efficient mechanism to achieve (a), but in
business transactions the existence decentralized ledger does not absolve the individual from (b).
In most online business transactions involving public keys the counter-party wishes to obtain assurance that the binding between a public-key and the subject legal name is correct and truthful. A self-asserted public key – as in the case of the PGP or SSI schemes – will be unacceptable to parties in a transaction because of an unfair burden of risk (e.g., one or both parties lie about their bindings, or one or both claim loss of their private-key immediately after signing a business agreement and repudiating the agreement). It is for this reason that the PGP model was never adopted by the business community.

It is also for this reason that the Certification Authority (CA) segment of the computer industry grew considerably starting in the mid-1990s - despite criticisms about the CA entities being "centralized". There was a business demand for a trusted third party to take on the liabilities of managing the X.509-based bindings between a public-key and its legal owner (i.e. the subject stated in the X.509 certificate). A major role of the CA entity is to undertake legal liability for the binding and to provide warranties in the case where an identity/key binding proved to be false or erroneous. The CA provided the mechanism for users to report key losses quickly, so that a stolen public key can immediately be placed on the certificate revocation list (CRL). The CRL database is accessible globally via standardized protocols and APIs (i.e., the Online Certificate Status Protocol and OCSP-Responders [41]). The role of the CA was thus to reduce the risk on the part of the transacting parties.

In the context of the architecture proposed in this paper, we explicitly and deliberately make a clear distinction between the globally unique identifier of a digital twin and any digital identity mechanism used to refer to ownership and accessibility rights on a digital twin. The DT-Container architecture provides a bridge to connect a digital twin with both an identity provider and an asset provider as two interconnected but clearly distinct parties.
9 EXAMPLE

To illustrate the concepts introduced in this paper we use a real-life implementation using the Compellio Registry middleware. The Compellio Registry middleware acts as a bridge between applications and systems managing assets (digital or physical). It implements the DT-Container features, acting as a middleware between legacy and blockchain systems where assets managed by the underlying systems are correlated to Digital Twins. Applications interact with the middleware to fetch Digital Twins and to consistently modify their states. Digital Twins participate in LUWs and the middleware takes care of related cross-system transactional coordination by modifying the state of Digital Twins across systems in a consistent manner.

The example presented below is borrowed from the domain of consumer product traceability and authentication. In the specific example, the digital twins are correlated to physical products.

9.1 Digital Twin state

As shown in Figure 4 the digital twins are defined in a declarative way. A ConsumerProduct is a digital twin that follows a life-cycle defined by various states (ConsumerProductState).

Figure 5 shows a visual representation of a digital twin on Compellio Registry middleware. In this specific case, the digital twin represents a ConsumerProduct instance (and more specifically, a wine bottle in the example). The state of the digital twin is defined by a set of attributes. The attributes are in the form of \(<\text{key}, \text{type}, \text{value}, \text{scope}>\) where scope is defined by three possible values: (i) private, i.e., attributes that are accessible by the owner of the digital twin; (ii) restricted, i.e., attributes that are accessible by users explicitly authorized by the owner of the digital twin; (iii) public, i.e., attributes that are accessible by any user. In the example below the attributes of the digital twin are related to the product (type of product, producer, year, wine kind, IoT “tag ID”, etc.). Figure 5 shows only public attributes. Users with special permissions can access protected and private attributes. The exact structure of the attributes and states of a digital twin can be formally defined by specific ontologies or other schema-driven definitions.

Note: As a special case, attributes can refer to other digital twins. In such cases, the attributes represent the relations to digital twins (referred by dt_ref type) already created in the system. See for example, attributes like acquired_by or consumed_by that are relationships to the digital twins referring to users.

9.2 Digital twin state registration

When a digital twin enters a new state, the state is registered on-chain. Figure 6 illustrates the details of the on-chain confirmation of the digital twin state registration.

Figure 7 illustrates the Ethereum transaction related to the registration of the constructed state of the digital twin. The digital twin gets serialized and the hash in registered on-chain via that transaction. The hash anchored on-chain appears in the Input Data attributes of the transaction.

Note: for confidentiality reasons, the hash of the serialized differs from the hash anchored on chain. Several ways of maintaining the link between the state hash and the anchored hash may be implemented, including for example, a timestamp [42, 43].

9.3 Digital Twin - state transition

When an application which is deployed on the DT-Container (e.g., smart contract managed by the Smart Contract Orchestrator or a software component deployed in the DT-Container of a non-blockchain Application Server) seeks to update the state of a digital twin, it calls the Repository component of the DT-Container by passing a new state to the digital twin.

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4https://compell.io/products/blockchain-registry
The Repository component then fetches the current state of the specific digital twin instance (\texttt{dat_ref_12345678} in the example below) and goes through verification of the DbCS state transition via the DT StateVerifer.

Let’s suppose that an application requests transition of the digital twin from state “Acquired” to state “Consumed”. The application requests to the Repository for the transition to the Consumed state, by way of passing a serialized state. Figure 8 illustrates such a transition. For the transition to be valid, the user that consumes the product must supply a consumption-code that is equal to the value of the consumption code attribute of the digital twin (nb. here we omit the UX process/details on how the operation is performed).

### 9.4 Logical unit of work

A Logical Unit of work manages ACID transactions among systems, where the Digital Twins and their underlying Digital Assets must be modified following an all-or-nothing principle. Figure 9 illustrates a case where DT-Containers are used to implement simultaneous execution of actions during acquisition of product, i.e., transition of the digital twin representing a product to the acquired state.

In this example we assume following:

1. The producer manages its inventory and integrates e-commerce transactions using traditional ERP software.
2. The producer is also using a customer loyalty service, offering digital tokens via a DLT.
3. The user holds an account in Digital Euros on a supervised financial intermediary (e.g., following a hybrid bearer digital euro and account-based infrastructure presented in [44]).
In the proposed architecture as shown in Figure 9, the DT-Containers are integrated with each of the three systems above. For the purpose of an example, assume that an e-commerce application implements a LUW – in which case the following actions must be performed in an atomic way:

- The product must be acquired (i.e., the digital twin moves to state `acquired` and the user is notified of its acquisition);
- The account of the producer is credited with digital euros for the value of the product;
- The loyalty account of the user is credited by the producer with some loyalty token, in accord with the customer loyalty program in place.

To perform this operation, the application initiates the LUW and makes use of the digital twins of the various systems. When all the above actions are performed the application requires completion of the LUW. At that moment, the DT-Containers are coordinating the consistent update of the underlying assets while ensuring that the correlated digital twins reflect the exact state of the assets.

10 RELATED WORK

In the past few years, there has been considerable interest and attention placed on the challenge of atomic swaps between blockchain systems, focusing primarily on permissionless (public) blockchains. Many atomic swaps schemes view the problem of digital asset management from a blockchain-centric perspective, ignoring the fact that in many use-cases the real-world assets truly
The basic notion in atomic swaps is the “swap” (trade or exchange) of one virtual asset to another in a concurrent interconnected manner. The basic two-party atomic swap using hash-locks in permissionless blockchains appears to have been first proposed in [45]. There are a number of issues around the notion of atomic swaps as defined using hash-locks in [45–47]. Firstly, each permissionless blockchain may have different throughput rates (i.e., block confirmation rates/speeds) based on the consensus protocol employed by each of the blockchains. This means that even with hash-locks and time-locks, additional synchronization mechanisms must be employed between blockchains (e.g., a centralized certified blockchain in [48]; witness blockchain in [49]). Secondly, many atomic swap schemes assume that the “value” of the assets does not change dramatically during the swap and settlement periods in the respective blockchains. However, the difficulty lies
During execution of a LUW the following actions are performed in an atomic way:
A user via an application (e.g. e-commerce) buys a product (managed by a traditional non-blockchain ERP system) using digital Euros from her account (managed by a supervised financial intermediary) and receives loyalty tokens (managed by a loyalty system with own blockchain back-end)

Fig. 9. Example of a LUW managed by DT-Containers involving coordination among both legacy and blockchain systems

in how to guarantee this value stability. Proposals such as [50] are effectively forced to introduce adjunct functions/services to address the value-stability problem.

The limitations of the smart contracts paradigm have also been discussed in [12]. One of the core ideas underlying the notion of smart contracts is the sharing of function and state information, where the ledger provides a universal sharing and accessibility to the shared state information. Both of these computing constructs are not new inventions ushered in by the blockchain revolution, but rather originate from the field of object-oriented programming (i.e., methods and private/public variables) [51, 52].

Related to our proposed use of DT-Containers for coordination, the Chainlink design offers a set of on-chain and off-chain components that allow smart contracts to interact with external sources. Chainlink provides smart contracts with the ability to push and pull data, facilitating the interoperability between on-chain and off-chain applications [53]. Off-chain nodes are responsible for collecting the data from the off-chain resource as requested by user contracts. After retrieving the relevant data, these nodes process that data through ChainLink Core, namely the core node software that allows off-chain infrastructure to interact with ChainLink’s blockchain. Once the data is processed, ChainLink Core transmits it to the on-chain oracle contract for result aggregation [53]. In our approach, we call for a fundamental modification of on-chain computations, introducing the notion of logical units of work and design by contract specifications as two foundation concepts in smart contract programming.

With regards to the need for the separation between structure from computation, the work on Obsidian [54] follows a similar approach to our current work, by making resources hold by a smart contract an explicit construct. Obsidian models the resources with linear types, which statically restrict the life-cycles, so that resources cannot be accidentally lost. Obsidian is a typestate-oriented language, representing state in types and statically preventing some invalid invocations. In our approach, the declarative definition of Digital Twin states follows the same objective by ensuring via post-conditions that computations maintain Digital Twins in consistent states.
11 CONCLUSIONS

In the current work we have proposed a more asset-centric view of blockchain systems and distributed ledger technologies, placing these technological components in their proper place within the broader computerized digital assets ecosystem.

Our novel contribution is that we move the central architectural focus from the application logic – implemented either in traditional application services or in smart contracts – to the Digital-Twin Container, which is one of the computing constructs aimed at maintaining the consistency of the assets between the off-chain world and the on-chain state digital twin representation. The notion of the Digital Twin Container is a cross-platform software framework that when deployed on a target system would offer the same set of technical capabilities regardless whether the underlying system is a blockchain/DLT or a traditional application server software stack.

The construct of the Logical Unit of Work (LUW) is used as the unit of processing of asset-related transactions and which must be completed atomically. The successful completion of a given LUW is achieved when all individual transactions in each system have been completed in a successful manner. In this sense, we rediscover and borrow from the proven paradigm of containers that originated from over two decades ago in the area of enterprise applications and which today have expanded into the containerization concept deployed currently in most cloud deployment infrastructures.

We expanded the role of cross-blockchain gateways to incorporate the DT-Container, and described an architecture that shifts core technical coordination capabilities into the portable DT-Containers. We thus simplify smart contract design into a layer that focuses on business logic applied to digital twins. DT-Containers – in collaboration with asset providers – handle all aspects related to consistency among digital twins and their correlated (physical or digital) assets.

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