Analysis of a Non-Fungible Token centric Blockchain Architecture and Comparison with a General Purpose Blockchain

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***Abstract*—Non-Fungible Tokens (NFTs) are among the most recent and promising additions to the blockchain universe. The usefulness of this concept triggered several public blockchain to offer support in this regard, starting with Ethereum, one of the popular and flexible blockchains. This support manifests itself through the ability of defining these tokens with smart contract programming. Ethereum defined itself as the reference for NFT development, establishing in the process token standards that are widely used today. This support also triggered the exploration of this concept through the development and deployment of NFT-based projects in the network, which created a rich application ecosystem, but it also revealed limitation in scalability and lack of sufficient throughput in the network. One attempt to solve these issues resulted in the creation of Flow, a new blockchain launched in 2020 that was built from scratch with NFT support in mind. This paper focuses in the alternative NFT architecture Flow introduces, namely, how it is structured, the main differences with a general solution such as Ethereum, and how a simple NFT contract implemented in this new paradigm compares with a similar implementation in Ethereum.**

***Index Terms*—Blockchain, Non-Fungible Tokens, Ethereum, Flow, Solidity, Cadence**

I. Introduction

The inspiration for Flow resulted from an experience from its creators, *Dapper Labs*, with the *CryptoKitties*, one of Ethereum's first NFT projects. This project extended the NFT concept with a new usability layer absent from similar projects. The contract minted a *CryptoKitty*, a NFT representing a digital cat-like creature, and each kitty token was characterised by a unique genome parameter, an internal 256-byte string from which the metadata of the token were derived from. The token metadata was then fed into an image generator that showed the kitty's characteristics. Parameters such as eye color, skin color, ear type, etc were encoded in portions of the genome string. The innovative aspect of this project was that two CryptoKitties could be "bred" to generate a new one with a genome string that derived from the parent's genome. Dapper Labs established the genome mechanics such that new traits were acquired somewhat randomly and some traits were rarer than others. This new approach translated into a peak of popularity and a surge in transactions submitted in Ethereum, and that end up exposing the scalability and throughput limitations of Ethereum [1].

Dapper Labs initially tried to solve these issues from within the Ethereum blockchain, but at some point it became clear that the blockchain needed architectural modifications to be able to overcome these throughput limitations. As such, instead of trying to "fix" Ethereum, Dapper Labs launched Flow in 2020 instead [2], a new blockchain solution developed from scratch centered around supporting NFTs and related mechanics. Flow presents several key differences from Ethereum, from how nodes behave in the network, the consensus algorithm used, to how data is stored and accessed in the chain, as well as similarities, such as defining and using a native cryptocurrency token to regulate blockchain operations (*gas* in Ethereum) and smart contract support. Yet, Flow claims to present the same level of NFT functionalities as Ethereum and other similar NFT ready blockchains, but approaching the concept from a fundamental different point.

This article introduces the Flow blockchain and its architecture, followed by the introduction and analysis of a pair of simple implementations of a NFT minter smart contract, one in Cadence, Flow's smart contract programming language, and another in Solidity, Ethereum's equivalent. Then we compare both architectures and implementations towards determining the merits of Flow's claims as a viable and optimised alternative from NFT-

based projects.

The rest of this article is structured as follows: Section II overviews the publications relevant to this work. Section III provides an introduction to Flow, the blockchain central to this exercise. Section V compares implementations of NFT smart contracts in both Cadence and Solidity, as well as the supporting blockchain architectures, namely Flow and Ethereum. This article concludes with Section VI.

II. Related Works

Non-Fungible Tokens were introduced about a decade ago with the Quantum project and got a boost when Ethereum and smart contracts appeared [3]. Even considering such small temporal window, the research community did produce a significant number of relevant publication that used NFTs in some capacity. The authors in [4], [5], and [6] explore a tokenisation approach to manage real estate, where houses, apartments, land plots, etc. are abstracted by NFTs. Real estate properties are unique and individual, similar to NFTs, and the blockchain mechanics that regulate these tokens are very similar to how real estate markets operate. [7] follows a similar approach where they use NFTs to abstract pharmaceutical products and use a *digital twin* approach to ensure the traceability by mirroring the lifecycle of a NFTs within a blockchain with the real product. This tokenisation trend continues with [8], where a similar strategy is used to propose a energy management system for microgeneration. The authors developed a blockchain-based environment where NFTs abstract actors in the system, i.e., solar panels, battery packs, wind turbines, consumers, utility companies, etc. and the values exchanged in the system, i.e., electric energy and money, are abstracted with fungible tokens instead (cryptocurrencies). [9] provides another example where an event management system uses NFTs to abstract event tickets, taking advantage of the same uniqueness and individual elements, such as allocated seat, event name, id number, etc, to individualise the token by encoding them into the metadata.

Others opted for a higher lever approach and presented an analysis based on the architectural aspects of NFTs rather than use them as a simple building block in a solution. [10] explores the architectural aspects of specific NFT implementations in the Hyperledger environment, a framework to develop private custom blockchains. [11] and [12] present a similar high level architectural approach but with a specific scope in mind, namely, tracing and value transfer applications. [13] and [14] presented *systematisation of knowledge (SoK)* articles about this technology, but they did not approached any architectural aspects. All publication mentioned thus far used Ethereum and Hyperledger for the examples provided, and none even mentioned Flow as an alternative. In that regard, to the time of this writing, we found no academic publications using Flow as a development platform, let alone exploring if the new architectural approach could benefit their solutions. The few mentions to Flow in academic examples came from review style papers, namely [15], [16], and [17], the latter providing the most extensive explanation of all.

A. Our Contribution

This paper presents a detailed exploration of the Flow blockchain as an architectural alternative to implement NFTs. To illustrate the differences, we also use Ethereum as an example of a general-purpose blockchain for comparison. We also present a concrete example of a simple NFT contract using Cadence, the smart contract programming language used in Flow, and compare it to a Solidity version of a functionally equivalent NFT contract. This exercise finalises with the analysis of the results obtained.

III. Flow Blockchain

This section goes into detail about the functional aspects of the Flow blockchain and assumes a general knowledge of blockchain technology from the reader and therefore, basic details about blockchain workings are omitted.

A. Consensus Protocol

Early blockchains implemented *Proof-of-Work (PoW)* as consensus protocol, where nodes solve cryptographic puzzles towards getting the privilege of publishing the next block and getting any rewards included. Before Flow, this protocol fell out of favor due to high levels of energy waste that PoW requires. Computations executed to solve these puzzles have no use whatsoever and the popularity of PoW blockchains such as Bitcoin exacerbated this issue.

The blockchain community reacted by proposing alternative consensus mechanisms, such as reputation based protocols like *Proof-of-Authority (PoA)*, and proportional protocols such as *Proof-of-Elapsed Time (PoET)* or *Proof-of-Stake (PoS)* were proposed as alternatives to PoW [18].

PoS became a popular alternative in 2020, around the time when Flow was being developed, which also coincided with Ethereum announcing a future fork (The Paris fork scheduled to 2022) to switch its consensus protocol to PoS. As such, Flow was created with a PoS consensus mechanism, joining a growing number of public blockchains using the same type of consensus.

B. Flow Node Roles

The scalability and throughput claims from Flow derive from an innovative four-node type architecture used to pipeline transaction processing in the network. Flow establishes four node roles, as opposed to the 2-node architecture used by Ethereum, which sacrifices some redundancy and adds a small increase in complexity in return for gains in speed, throughput and scalability, while maintaining minimal operational costs.

The Flow network is based in *consensus nodes* that decide the presence and order of transactions in the blockchain; *collection nodes* used to enhance network connectivity and data availability for applications; *execution*

nodes to perform the computations required in transactions; and *verification nodes* to validate outputs returned from the execution nodes [19]. Delegated computations are validated with *Specialised Proofs of Confidential Knowledge (SPoCK)*, a type of non-interactive zero-knowledge proofs based on the *Boneh-Lynn-Shacham (BLS)* signature scheme developed by Flow creators for this specific purpose [20].

C. Cadence Language

Cadence is the programming language to write smart contracts in Flow, as well as scripts and transactions required to interact with deployed contracts in the network. Ethereum uses Solidity exclusively to write smart contracts. To interact with a deployed contract in Ethereum, users have to rely in Ethereum's API and interact with it using scripts written in general purpose languages such as Javascript and Python. Flow simplifies this by using Cadence for both smart contract development and to interact with deployed instances in the network. Cadence implements a *Resource Oriented Programming Paradigm* through a strongly static type system, with built in access control mechanics that can be further specialised through a *capability-based* security scheme that can narrow the scope of users allowed to interact with a given resource. Cadence syntax was inspired by modern general-purpose programming languages such as *Swift*, *Kotlin*, and *Rust* [21] [22].

1) Smart Contracts: Smart contracts in Flow serve the same purpose as in Ethereum and other blockchains with similar support. Flow contracts are syntactically different from Solidity, but functionally they are very similar: both use the **contract** keyword to define the main contract structure, use constructor functions that executed automatically once during deployment and can extend their functionalities by importing external contracts and interfaces. But, unlike Solidity, Cadence does not require the implementation of default destructors because storage management is automatically managed. Smart contracts deployed in Flow remain in an "updatable" phase initially. During it, the code can be updated by the creator(s). Once the developer(s) are satisfied with the contract's performance, they can *lock* it to prevent future changes. This allows for cleaner deploys and optimise blockchain storage, unlike Ethereum that saves any new versions of an existing contract in a new block, which can clutter the blockchain with useless code.

2) Interacting with Flow Smart Contracts: In Flow, if an interaction is limited to read operations, i.e., the script instructions **do not change** the state of the blockchain, then a *script* should be used. If the instructions do **change the state** of the blockchain, by saving, modifying or deleting data, a *transaction* needs be used instead. *Transactions* require a valid digital signature and funds allocated to pay for gas costs. Flow restrict modifications to digital objects in storage to only the owner(s) of such object, therefore transactions that do these changes require a digital signature from the owner. *Scripts* on the other hand, are "free" to execute because they do not consume gas, therefore they do not require signatures and are used to read public parameters in a contract.

3) Resource Oriented Paradigm: Cadence establishes its programming paradigm through a special digital object named *Resource* which was inspired by Rust's *linear types*. From a functional point of view, Cadence resources are similar to objects in Object-Oriented programming languages. The difference resides in the control exercised by the language to ensure that Resources are unique in a blockchain environment. Once created, a resource cannot be copied; only moved or destroyed. Since resources cannot be copied, they also can only exist in one location at a time, often saved in an account's storage area. Only functions defined in smart contracts can create resources. Cadence limits the scope of the **create** keyword used to create an resource to a smart contract. Flow smart contracts are deployed with resource creation functions which then are invoked using transactions, since creating a resource changes the state of the blockchain. So far, resources are exclusive to Flow, which is a limiting factor to establish interoperability with other blockchains.

4) Cadence Types: Cadence uses basic types, similar to Solidity, for elements such as integers, strings, floats, etc. The nomenclature is slightly different than in Solidity. For example, an unsigned 256 bit integer in Solidity is denoted by **uint256**, while the Cadence equivalent is **UInt256**. Complex elements, like resources, events, structs, etc., have complex types that result from concatenating the contract name with the element. Since complex elements can only be created through a contract functions, Flow uses this to its advantage. Pairing the contract name with the resource name creates a unique identifier by default. This ensures type uniqueness withing Flow projects since contracts in the same storage space require different names. To uniquely identify a resource in the blockchain, this nomenclature extends to include the address of the deployed contract as a prefix to the type. For example, a withdraw event emitted is logged as `A.0ae53cb6e3f42a79.FlowToken.TokensWithdrawn`.

This complex type results from the concatenation of the deployed contract address(0x0ae53cb6e3f42a79), the name of the contract(FlowToken), and the name of the event(TokensWithdrawn) to create a string that identifies a specific, unique element in the chain.

5) Capabilities and References: Cadence provide a fine-tune access control mechanism through a object-capability model. Similar to traditional capabilities, these are a value that represents the authorisation to access and operate on a digital object. Capabilities in Cadence divide into *storage* and *account* types. Capability issuing is limited to the owner of the resource or account targeted and are stored in a special `\public` domain area available for public access but restricted to store capabilities. Sec. III-E1 provides

additional details in these domains. After publishing a capability to the `public` domain, another user can "borrow" it. *Borrowing* in Cadence retrieves a reference to a stored object through a previously published capability. References in Cadence are akin to memory pointers in general purpose programming languages. References are used to read data from stored objects without accessing the object directly, thus protecting it against deletion and unauthorised transfers.

6) Access Control: Cadence implements access control in two levels of granularity. At a coarser level, contracts and objects limit the access to their inner constituents, e.g., functions, parameters, structs, etc., using the **access** keyword, with the scope of access inside parenthesis. **access(all)** grants public access. **access(E)**, where E is an entitlement restricts access to only users with such entitlement. **access(account)** limits the scope of access to other functions and objects saved in the same account, while **access(contract)** narrows the scope to the same type of elements, but limited to the same contract. The most restricted level is **access(self)**, which restricts access to functions and parameters defined within the element affected.

a) Entitlements: Entitlements complement the second level of access by providing granular access control to individual members (fields and functions) of a composite object, namely a resource or a struct. Entitlements can be used to create references to stored resources and structs with different "versions", i.e., the digital object referenced is the same but the sets of fields and functions available are different for each entitlement. Cadence uses *auth(entitlement)* to specify the entitlement to use during the resource retrieval process and '&' to identify a reference to a resource, while'@' is used to denote the resource itself. For example, consider a *Resource* R with two fields: *access(A) name* and *access(B) age*, where A and B are custom entitlements defined in the contract where *Resource* R is defined. With a resource R in storage, retrieving auth(A) &R returns a reference to R where only *name* is accessible. Conversely, retrieving auth(B) &R returns a reference to the same resource, but with only *age* available. Entitlements can be combined using 'and' or 'or' logic: *access(A, B) name* sets *name* to require entitlements A **and** B, while *access(A | B) name* changes the requirement to either entitlement A **or** B.

D. Token Standards

Flow standardise its fungible and non-fungible projects by defining contract standards, similarly to Ethereum. Flow developers followed Ethereum's approach in publishing contract standards as interfaces, but they also took the opportunity to name them more suggestively. As such, Flow regulates fungible tokens applications with the *FungibleToken* standard [23], Ethereum's *ERC-20* equivalent. Non fungible tokens have a corresponding *NonFungibleToken* standard [24] that mirrors Ethereum's *ERC-721* standard. These standards have the same function as in Ethereum, i.e., they guarantee the implementation of parameters and functions defined in the standard, which Flow uses to ensure interoperability within the application ecosystem.

E. Account-based Storage Model

Flow implements an *Account-centric Storage Model*, different from the *Contract-centric Storage Model* used in Ethereum. Storage locations are indexed from an account address and the amount of storage space per account is proportional to the amount of FLOW token in balance, currently at a rate of 1 FLOW token per 100 MB of storage. An account in Flow is, essentially, a digital object that needs to be saved in the blockchain itself. This requirement establishes that accounts in Flow require a minimum of 0,001 FLOW to be operational, the amount required to sustain the basic structure of an account in the blockchain. This is also the fee to create a new account in Flow, though a newly created account comes with 0.001 FLOW already in its balance. At the time of this writing, FLOW price oscillates between 0.5 and 1$ per token.

1) Storage Domains and Paths: An account in Flow is a digital object identified by an address, contains a *balance* and a set of *public encryption keys* used to validate transactions signed by the account owner. The storage area associated to the account is split into contract storage, where smart contracts are stored, and a general purpose storage area to save other digital objects, such as NFTs and other resources.

The general storage space is divided into three domains: a `\storage` domain only accessible by the account owner and where all data is actually written into; a `\public` domain to store the *capabilities* in Sec. III-C5, therefore limited to read-only access; and a `\private` domain used for capability storage also, but this one restricted to the owner.

Object are stored using UNIX-style paths, with the storage domain as the first element. For example, `\storage\ExampleNFT` indicates an "ExampleNFT" resource stored in the main storage domain, while `\public\ExampleNFTCap` indicates a capability published as "ExampleNFTCap" in the public domain that can be used to retrieve a reference to the ExampleNFT in `\storage`.

2) Resource Collections: The storage system described in Sec. III-E1 is not flexible if a large number of resources are to be stored. Like UNIX paths, storage paths in Flow need to be unique in each account, which can complicate the storage process as more objects are sent to storage. Flow was developed around the concept of digital collectibles, with the expectation that accounts would hold large numbers of NFTs or other resources. To solve this limitation, Flow uses a special resource called *Collection*. Essentially, a collection is a resource that can save and hold other resources in storage, are standardised

in Flow through the *NonFungibleToken* standard and each collection is limited to store resources of one type. Collections needs to be created and saved in a unique storage path, but after that, other resources go in and out of a collection using *deposit* and *withdraw* functions, using token identification numbers to identify the token in question instead of having to create a new and unique storage path for each new resource. In UNIX analogy, collections behave akin to directories.

IV. Development of a NFT Smart Contract in Cadence

The approach in this section assumes a minimal knowledge from the reader about general blockchain technology and NFTs development in Solidity. As such, we opt to omit the implementation details from this blockchain and focus this text to the unfamiliar Cadence version. Fig. 1 presents a schematic representation of the contract developed displaying the required standard dependencies and the functions and fields required by this inheritance.

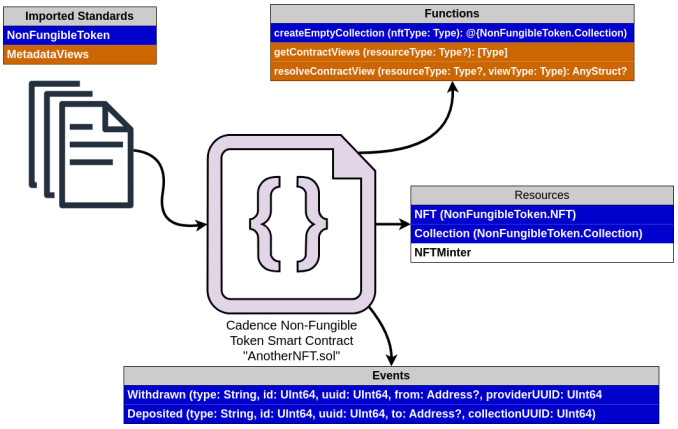

Figure 1. Structural organisation of a NFT smart contract in Cadence

A. Standards Imported

The simplest standardised version of a Cadence NFT smart contracts requires the import of two standards, namely, *NonFungibleToken* and *MetadataViews* interfaces. We omitted references to the *MetadataViews* because this import is an imposition from the *NonFungibleToken* import. Flow was developed towards supporting applications with high NFT throughput, such as digital collectibles for example. The *MetadataViews* standard is used mostly to support metadata operations, which are used extensively in Flow to compose digital collectible objects similar to trading cards. This functional aspect falls outside the bounds of our study, so most of the requirements from this standard were ignored. We used a color scheme in Fig. 1 to indicate which standard required the function, resource and event indicated in the contract structure. The *MetadataViews* requirements, since they are used to process token metadata, were implemented as stubs.

1) Resources: The *NonFungibleToken* standard requires the implementation of NFT and a Collection resources as minimal requirements. But Fig. 1 shows a third resource in the contract, namely a *NFTMinter*. This resource is used to abstract, simplify and secure the minting of new NFTs. New resources can only be created with a contract function due to Cadence restricting the "**create**" keyword to the context of the contract. Transactions are not able to invoke this internal action by themselves. The creation of new resources is restricted to contract functions. A secure and simple approach to resource creation is to define the create function inside of another resource and created and save it to owner account storage in the contract constructor. This restricts the creation of new NFTs to the owner of the account storage where the minter is saved, thus decoupling this action from the contract itself.

2) Functions: The *NonFungibleToken* standard requires the implementation of a *createEmptyCollection* function to obtain a collection resource, but it also requires similar implementations in the NFT and even in the collection resource itself. Standardised NFT contracts in Flow provide multiple access points to create new collections. The *createEmptyCollection* function at the contract level requires a type as input because it is not possible to infer the storage type at that level. The versions at the resource level can infer the storage type by checking the type of the resource that is housing it.

3) Events: A contract that imports the *NonFungibleToken* inherits the *Withdrawn* and *Deposited* events by default. In Cadence, like in Solidity, events are made available and emitted automatically by the logic imported from the standards, i.e., there is no need to define them explicitly in the contracts, unlike functions and resources. The events indicated are emitted automatically whenever a NFT resource is moved in or out of an account storage.

V. Results and Comparison

A. Blockchain Comparison

Flow implements a different architecture and it is purpose oriented unlike a general purpose blockchain like Ethereum. Table I presents an objective comparison between the architectural differences between the solutions.

The technologies are similar in their general approach: both implement a fungible token as cryptocurrency and use it as gas towards optimising virtual machine computations. The term *gas* was introduced in Ethereum, butFlow implements the same exact logic, though they refer to these costs as simple *transaction fees*. Ethereum spent the first 9 years using PoW to achieve node consensus, like Bitcoin, but the Paris fork from September 2022 implemented the *Ethereum Improvement Proposal 3675 (EIP-3675)* which switched the consensus protocol to PoS [25].

Both blockchains define smart contract programming languages to produce code that can only execute in the respective distributed virtual machines. The languages

Table I
ETHEREUM-FLOW TECHNOLOGY COMPARISON

Parameter	Non-Fungible Token Architecture	
	Ethereum	**Flow**
Year	2013	2020
Cryptocurrency	ETH	FLOW
Programming Language	Solidity	Cadence
Consensus Algorithm	2013-2022: PoW, 2022-: PoS	Proof-of-Stake (PoS)
Network Nodes Roles Types	1 - Execution Client	1 - Collector Node
		2 - Consensus Node
	2 - Consensus Client	3 - Execution Node
		4 - Verification Node
Token Standards	ERC-20 (fungible token)	FungibleToken
	ERC-721 (non-fungible token)	NonFungibleToken
Data Storage Architecture	Contract-based	Account(User)-based
Block Rate (Average)	12 - 15 seconds per block	0.5 - 1 seconds per block
Daily transaction volume (2024)	1 - 1.25 million transactions\day	0.5 - 1 million transactions\day
Cost per transaction (average)	5.5 gwei (∼0.39 $)	∼0.00000845 $

have distinct syntaxes, but produce digital elements with similar behaviours and functionalities. Flow justifies their higher throughput, low operational costs and higher scalability on their four node pipelining architecture. Essentially, Flow doubles the roles in Ethereum's two-node architecture to establish a more efficient, but also more complex, node architecture.

Flow is the cheapest and fastest of both, with a block rate between 12 and 30 times higher and with transactions, 46154 times cheaper than Ethereum's. Yet, Ethereum's popularity and maturity still trump over Flow's operational advantages. At the time of this writing, Ethereum daily volume of transactions are up to 2.5 times higher than Flow. It appears that popularity and ecosystem maturity influence technology adoption more that efficiency and cost, at least in a short term basis. It is important to notice that Ethereum has been available for twice as much time as Flow, and Flow had to compete with other newly created blockchain at a level that Ethereum never had to. But from the performance point of view, the superiority of Flow is clear.

B. Contract Implementation Details

We developed two smart contracts in Solidity and Cadence implementing the *ERC-721* and *NonFungibleToken* standards respectively, and used them to execute the following sequence of macro actions:

1) Deploy the NFT contract in a network
2) Mint a NFT into a user account
3) Transfer the NFT from one user account to another
4) Burn the NFT

This sequence of actions were relatively straightforward to execute in Solidity. Flow had some overhead that had to be dealt with first, namely the creation of additional accounts and the creation of a collection resource, as indicated in Sec. III-E2 in each account, unlike in Ethereum. Though it is possible to save a NFT directly into a storage path in flow, we opted to include collections to illustrate the overhead impact in Flow's version of the process.

C. Cost Comparison

We begun the comparison exercise by analysing how much gas was consumed in each of the steps considered. Ethereum gas calculations are easier since development frameworks often include gas calculation tools that keep track of the balance of the accounts throughput a series of transactions. We used Hardhat, a popular development framework for Ethereum, for this purpose and a built-in *gas reporter* tool to determine the gas expenditure. Table II displays the results:

Table II
GAS CONSUMPTION REPORT FROM HARDHAT'S GAS REPORTER TOOL.

Solc version: 0.8.24		Optimizer enabled: false		Runs: 200	Block limit: 6718946 gas	
Methods						
Contract	Method	Min	Max	Avg	# calls	eur (avg)
ExampleNFT	burn(uint256)	-	-	29592	1	0.8091
ExampleNFT	safeMint(address, uint256, string)	-	-	121859	2	3.3312
ExampleNFT	safeTransferFrom(address, address, uint256)	-	-	58401	2	1.5973
Deployments		-	-	2420549	36 %	66.205
ExampleNFT		Totals		2630401		71.943

The *gas reporter* was connected to a cryptocurrency pricing oracle to obtain the gas costs in EUR in real time from off-chain data sources. ETH price currently is very volatile. We present them mainly to illustrate the difference, especially compared to a much cheaper option of Flow, rather than infer over their absolute value. Flow's development framework does have a *gas reporter* comparable feature but determining the balance of an account is quite easy. As such we calculated these fees directly by subtracting account balances between steps. But in Flow there is another simple method to determine costs. Flow imposes a base dependency to all standardised contracts to a contract named *FlowFees*. This contract is required in every Flow standard, including the *NonFungibleToken* used, to automate fee computations. The contract also emits a *FeesDeducted* event every time any fees are deducted from an account. The event is emitted with the amount paid as argument, so we can also captured these events to validate the values calculated. We used this method to produce Table III with the fees paid in Flow:

1) Analysis: A quick analysis reveals that, even with some overhead included, Flow is cheaper to operate than Ethereum. Table III reveals that most transactions cost the same value of 0.00001 FLOW. This is the minimal fee established in Flow [26], which can mean that the transaction cost was actually lower than that. Flow's fee system

Table III
FLOW TOKEN BALANCE OF EACH ACCOUNT IN THE EXERCISE

FLOW token balance of accounts						
Tx	**Emulator-account**		**account01**		**account02**	
	Balance	Difference	Balance	Difference	Balance	Difference
00	9.99600		0		0	
01	9.99396	-0.00204	0.001	0.00100	0.001	0.00100
02	7.99392	-2.00004	1.001	1.00000	1.001	1.00000
03	7.99390	-0.00002	1.001	0.00000	1.001	0.00000
04	7.99388	-0.00002	1.00099	-0.00001	1.00099	-0.00001
05	7.99386	-0.00002	1.00099	0.00000	1.00099	0.00000
06	7.99385	-0.00001	1.00098	-0.00001	1.00099	0.00000
07	7.99384	-0.00001	1.00098	0.00000	1.00098	-0.00001

Transactions
00 – New service-account created
01 – Emulator test accounts created (2)
02 – Emulator test accounts funded with 1.0 FLOW
03 – Deploy ExampleNFTContract into emulator
04 – Create a NonFungibleToken.Collection in each account
05 – Mint an ExampleNFTContract.NFT into account01 Collection
06 – Transfer ExampleNFT from account01 to account02
07 – Burn the ExampleNFTs from account02

is based in three fee factors: an *inclusion fee (IncFee)* to pay for the process of including the transaction into a block, transporting information, and validating signatures in the network; an *execution fee (ExecFee)* to pay for FVM computations and operating on data storage, and a *Surge fee (SrFee)* applied dynamically to modulate network usage and avoid surges. The total transaction cost can be calculated with: $TxCost = (ExecFee + IncFee) \times SrFee$. If *TxCost* is less than the minimal fee, TxCost is ceiled to that value instead.

Currently, the inclusion fee is fixed to 0.000001 FLOW, thus less than the minimum fee, and the surge factor is included in the transactional costs formula, but it is not yet available in mainnet. This means that, currently, transaction fees in Flow are mostly influenced by the computation effort required. But Table III shows that these do not exceed the minimum fee per transaction established in most cases. Contract deployment and creating new accounts are the most expensive operations. The deployment transaction cost is proportional to the size of the contract in question, which for our case amounts to 6730 bytes of storage. Flow's documentation only specifies storage costs for data in general but not for contract storage. But it estimates the cost of a deployment of a 50 KByte contract to be 0.00002965 FLOW. Our contract is substantially small, therefore the fee requested is coherent with the logic so far. The documentation also confirms that account creation is indeed the most expensive of all of Flow's base operations, though a lot of that cost derives from the requirement that new accounts are created with a balance of 0.001 FLOW and that has to be paid by the account creator. Without that value, the account creation process costs 0.00002 FLOW per account, or two minimal fees.

The similar exercise in Solidity required less transactions but it cost almost 72 €. Flow required extra operations to bring the system up to par, but even with that, the total amounts to 2.00216 FLOW (around 1.72 €), a reduction by a factor of 42 compared to Ethereum. The Flow cost is actually a very conservative estimation of sorts. It includes 2.0 FLOW that were transferred to the two extra accounts to increase their balance above the minimum of 0.001 FLOW so that these could pay for transactions without dropping the balance lower than the required minimum. Given how cheaper transaction costs are in flow, this could have been a lower value without risking the operation. On a cost basis, Flow is clearly the preferable option.

D. Storage Comparison

Storage is a critical aspect in blockchain applications. Writing into a blockchain block is expensive because data is replicated in all network nodes. Considering the importance of blockchain data storage, particularly to NFTs that use this (meta)data to establish properties, we run a similar analysis towards determining the storage space consumption in the exercise thus far.

1) Storage in Ethereum: Ethereum use a *contract-based* approach to store data, which means that all contract data is stored *referenced* to the contract deployment address. Ethereum defines an "astronomically large array" indexed from the deployed contract address as the storage space of the contract. This array has 2^{256} potential slots, which is a number close to the number of atoms in the visible universe, hence the "astronomical" adjective, and each index in the array can store up to 32 Bytes [27]. The "potential" derives from Ethereum only storing non-zero values, i.e., if a contract parameter has value 0, it does not count to the total storage used by the contract. Contract parameters are stored sequentially from index 0 but mappings, due to their dynamical nature, distribute their data throughout the storage space. Mapping values are stored in a position obtained from a digest from a hash function applied to the mapping key concatenated with a positional index, which means that mapping data is not stored in sequential position in the storage array, This complicates the storage analysis since Ethereum nor Solidity provides a direct way to determine the storage used. So, we had to devise a method that takes this into account to calculate storage values. We used a custom script that checks storage slots for data, i.e., non-zero values and included our findings in Table IV:

The lion share of used storage is clearly the deployed contract. Hardhat also provides a *size-contracts* feature that returns the storage occupied by each deployed contract, which simplified this step. The remaining values were found by running a storage scanning script to determine how many slots were in use and the amount of data stored in each. The *Simple Storage* column refers to contract parameters such as *totalSupply*, *nextTokenId*, etc, while the *Mapping Storage* refers to values stored in mappings. All mappings in the ExampleNFT contract are only used for the purpose of establishing token ownership,

Table IV
STORAGE ANALYSIS OF THE SOLIDITY NFT CONTRACT

Tx	Storage used by the ExampleNFT Solidity contract			
	0x5FbDB2315678afecb367f032d93F642f64180aa3			
	Contract Size	**Simple Storage**	**Mapping Storage**	**Total**
00	10458	96	0	10554
01		128	94	10680
02		128	94	10680
03		128	0	10586

Transactions
00 - Deploy ExampleNFT Contract into the emulator
01 - Create an ExampleNFT into account01
02 - Transfer ExampleNFT from account01 to account02
03 - Burn the ExampleNFT from account02

which is confirmed in Table IV. The NFT only "exists" in transactions 01 and 02 and that is reflected in the presence of mapping storage. Once the token is destroyed (burned) this data is deleted.

2) Storage in Flow: Storage calculations are simpler in Flow. Flow accounts have a storage parameter that is is trivial to obtain, similar to the balance. We developed a simple script to determine the space used by each account after each step and use the results to construct Table V:

Table V
FLOW TOKEN BALANCE OF EACH ACCOUNT IN THE EXERCISE

Tx	Storage used by Flow accounts (Bytes)					
	Emulator-account		**account01**		**account02**	
	Storage (Bytes)	Difference	Storage (Bytes)	Difference	Storage (Bytes)	Difference
00	428655		0		0	
01	429290	635	1007	1007	1007	1007
02	429607	317	1007	0	1007	0
03	436337	6730	1007	0	1007	0
04	436613	276	1588	581	1588	581
05	436769	156	1751	163	1588	0
06	436894	125	1588	-163	1751	163
07	437035	141	1588	0	1588	-163

Transactions
00 – New service-account created
01 – Emulator test accounts created (2)
02 – Emulator test accounts funded with 1.0 FLOW
03 – Deploy ExampleNFTContract into emulator
04 – Create a NonFungibleToken.Collection in each account
05 – Mint an ExampleNFTContract.NFT into account01 Collection
06 – Transfer ExampleNFT from account01 to account02
07 – Burn the ExampleNFTs from account02

The emulator-account displays an unusual large used storage but this is not relevant for our exercise. To speed up and simplify development, Flow provides its emulator environment with a series of standards already deployed into this account storage area, hence the large value at startup.

3) Analysis: Flow presents itself as a more efficient alternative to save data in a blockchain. Ethereum saves data in 32-byte chunks arranged sequentially from the deployed contract address. To optimise storage, when possible, Ethereum saves two values into the same slot, if both are 16 bytes or less, by splitting one 32-byte slot into two of 16, but overall, apart from contracts, Ethereum saves data "discretely", i.e., in 32 or 16-byte chunks, except for strings, which are saved in UTF-8 using 2 bytes per character. Flow on the other hand presents a more granular storage, where data is discriminated to the individual byte.

Regarding the size of the NFT construct itself, Ethereum is the better option in the sense that it produces a smaller data footprint. The NFT created in Flow was blank, i.e., without any additional metadata other than the bare minimum required by the standard, while the version in Ethereum was created with the recipient account address as metadata, stored as a UTF-8 string, also to illustrate the differences. Ethereum NFT was computed at 94 bytes of storage, including a 32-byte string as metadata, while a programmatically smaller NFT from Flow required 163 bytes. Flow has a significantly more storage overhead than Ethereum, but it still maintains a higher transactional throughput nonetheless. Though Flow does require more storage in absolute values, price for storage in Flow, both in storage and transaction fees, is much less than in Ethereum, which diminishes this disadvantage.

Overall, Flow is still the better option in this case. Storage in Ethereum is a complicated issue in great part because of how expensive ETH has become as well. Also, this chain has a slower block rate than Flow, which means a lower rate of data writes. Flow does write more data to achieve similar functionality, but does so in a inexpensive and faster fashion, which skews the preference to its direction.

VI. CONCLUSION

This paper presents an implementation analysis for two distinct architectures used to create NFT-based contracts. Ethereum and Flow were chosen for this exercise due to former's role as a general-purpose and popular blockchain used as reference, the latter a specific blockchain created to solve known throughput and scalability issues with Ethereum.

Despite being significantly younger than Ethereum, Flow provides enough features to produce NFT-capable contracts. The structural analysis in Sec. III reveals Flow as a more complex, but also more configurable blockchain. From a programmatic point of view, Cadence is syntactically more complex, contracts consume more time to develop, but the deployment process is simpler, faster and produce smaller deployable code than the Ethereum equivalent. The cost aspect favors Flow as well, though the limitations of Ethereum in that aspect fall outside of the technological scope considered. Flow's lack of relative popularity works in its favor by providing a cheaper and realistic alternative to NFT-based applications since FLOW's price is not as affected from the same speculative forces that risk making Ethereum too expensive to use.

Though Flow offers clear advantages, Ethereum still has the lion share of the NFT-based applications in the blockchain ecosystem. The 7 years that Ethereum has on Flow are a significant gap to overcome. Ethereum was the only realistic option for smart contract development for a long time, which boosted its popularity to levels difficult to replicate. Nevertheless, Flow does present a rich, albeit limited, application ecosystem focused on digital collectibles, which is the type of applications suitable for a NFT intensive blockchain.

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