NFTs: Tulip Mania or Digital Renaissance?

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Abstract—Galleries, Libraries, Archives and Museums (GLAM) institutions have begun to sell non-fungible tokens (NFTs) of works from their collections following the $69.3 M USD record sale of Beeple's *Everydays: The First 5000 Days* at Christie's auction house on March 11, 2021. But many open questions exist about whether NFTs are beneficial or harmful for such institutions from financial, regulatory, and environmental perspectives. In this paper, we aim to unpack what NFTs are within the context of tokenomics and Ethereum standards development by providing an overview of notable NFTs and selling platforms before discussing the pros and cons of their use in GLAM institutions and exploring open research challenges through the lens of Computational Archival Science. Methodologies for the creation (minting) and purchase of NFTs are provided, emphasizing NFTs' record keeping abilities, while also highlighting their inherent vulnerabilities, particularly with regards to the now-infamous *broken link problem* and its implications for provenance tracking and authenticity.

Index Terms—nonfungible tokens, blockchain, smart contract, distributed ledger, digital art, provenance, tokenomics

I. INTRODUCTION

Galleries, Libraries, Archives and Museums (GLAM) institutions have begun to sell NFTs of works from their collections. The British Museum, for example, is one of several GLAM institutions that has recently sold non-fungible tokens (NFTs) [1]. True to the predication in [2] that blockchain-based tokenization could truly transform the fundamental nature of archives, by once again seeing them become stores of treasure, or treasuries, as they were in medieval times, NFTs are bringing about that transformation. Indeed, some argue that GLAMS are sitting on a treasure trove of 'NFT-able' digital assets because of their large collections of archival documents, art, culture, pop and design. Furthermore, archives and other GLAM institutions will likely need to manage NFTs that they have received as donations (e.g. the ICA Miami and the gift of CryptoPunk 5293 from one of its trustees [3]). While much of the buzz and concern about NFTs in the GLAM "Twittersphere" has revolved around the ethics of selling NFTs based on works from their collections - with those in favour tending to see NFTs as an innovative democratization of works and a means of generating new sources of revenue for cash-strapped GLAMs and those against seeing NFTs as crass commercialization and hype culture at its worst - it is all too easy to become distracted by the buzz of crypto-economics, or "tokenomics." For GLAM institutions whose holdings might one day include these types of digital assets, however, there are fundamental questions relating to authoritativeness, intellectual property, copyright, and long term preservation of NFTs that are equally pressing to answer.

II. WHAT IS AN NFT?

An NFT, or non-fungible token, is a unique, digital object certified on a blockchain or distributed ledger, typically Ethereum. Following Ethereum's creation in July 2015, the term NFT was coined in the (Ethereum Request for Comments) ERC-721 Ethereum Standard, published January 24, 2018, after "community consensus" to represent a "diverse universe of assets," including physical property, virtual collectibles, and negative value assets such as loans or responsibilities [4]. As NFTs have increased in value, recent NFT owners have put them up as loan collateral. The other term for NFTs, 'deed,' has not received the same popularity but is considered particularly appropriate for physical assets such as land titles. Other terms considered, but ultimately rejected, include 'distinguishable asset,' 'title,' 'token,' 'asset,' 'equity,' and 'ticket:' terms which emphasize the link between Ethereum smart contracts and traditional contract law. The emphasis is on tradeable assets: digital, physical, or both. For example, NFTfi (NFTfinance), "a pawn shop for NFTs," allows owners to stake their NFTs for more fluid cryptocurrencies; unfortunately, there have been reports of such owners defaulting on these loans, sometimes with the NFT now worth more than the original stake [5].

Although other blockchain platforms besides Ethereum can support NFTs, as of October 2021, only the Singaporian-centric open source blockchain, TRON, founded by Justin Sun, CEO of BitTorrent, has created its own non-Ethereum NFT standard. Launched December 24, 2020, (TRON Request for Comments) TRC-721 was created to mirror Ethereum token standard, ERC-721: as with the ERC-20 standard, existing token standard TRC-20 was found to be insufficient for tracking unique tokens, i.e., NFTs [6].

Fungible tokens, conversely, are akin to currency: a dollar is a dollar is a dollar as the saying goes. A cryptocurrency such as Bitcoin (BTC), as a fungible token, is interchangeable (non-unique) and holds the same face value as other tokens of the same type. Fungible tokens can also be subdivided into smaller units of value. In contrast, a non-fungible token is not intended to be divisible, since the value of such tokens is typically

	Fungible	NFT
Type	Interchangeable	Unique
Divisible	Yes, as in cryptocurrency	Not traditionally, but an item can be divided into multiple NFTs sold separately (eg. Maecenas) Emergence of fractionalized NFTs (f-NFTs) may be considered a fungible security
Conversion	Can make an NFT of an instance of a fungible token, similar to Colored Coins	Can pay for NFTs using fungible cryptocurrencies, stake a loan collateral

based upon the entirety of an asset. For example, traditionally an artwork would not be the same artwork if it were to be divided into smaller parts. Nevertheless, Ethereum-based start-up Maecenas is trialing a fractional ownership model in its first auction of Andy Warhol's *14 Electric Chairs* [7] and Beeple's *Everydays* is itself composed of 5,000 NFTs, one for each 'day' that was then minted and sold as one NFT on March 11, 2021 [8]. Furthermore, on March 16, 2021, the first auction of fractionalized NFTs (f-NFTs) occurred on *fractional.art*, whereby NFTs were broken down and sold as fractions of the original purportedly to "democratize" NFTs and increase their liquidity [9]. f-NFTs, then, bridge between NFTs as collectibles and fungible cryptocurrencies as securities in the Decentralized Finance (DeFi) sphere: the end game of art as a commodity. A comparison of fungible versus non-fungible tokens is provided in Table I.

III. A BRIEF HISTORY OF NFTS

The first NFT was posed as an art experiment at a hackathon portion of New York-based conference, *Seven on Seven* on May 2, 2014 [10]. Digital artist Kevin McCoy registered a video clip subsequently sold to his hackathon partner, Anil Dash for the contents of Dash's wallet: $4 USD. This "monetized graphic" required the use of Bitcoin-forked blockchain, Namecoin (NMC), designed to act as a decentralized Domain Name System (DNS).

Subsequent digitally native tradeable blockchain artworks such as Rare Pepes (est. 2016, Counterparty [11]) and Curio Cards (considered the first art related NFTs, launched in an online artshow on May 9, 2017 [12]) were presented as collectible trading cards. However, as noted by Ethereum in their ERC-721 standard [4], they "are not distinguishable assets [but rather] a collection of fungible tokens, each of which is tracked by its own smart contract with its own total supply." Nevertheless, in February 2021, the so-called 'Rarest Pepe,' HOMER PEPE, a Homer Simpson-Pepe mashup in the form of a collector's card, was sold as an official Ethereum NFT for $320k USD (205 ETH) [13].

As noted on their website, CryptoPunks (est. June 2017, Larva Labs [14]), represent the first example of NFTs on the Ethereum Blockchain, and claim to be the inspiration for both the ERC-721 standard, and the CryptoArt movement as a whole. Focusing on rarity, a limited run of 10,000 unique CryptoPunks utilizing the Ethereum ERC-20 token standard were initially free to be claimed for anyone with an Ethereum wallet. CryptoPunks, however, have been subsequently resold throughout their history for increasingly larger sums [29]. At *Natively Digital: A Curated NFTs Sale*, a Sotheby's auction of firsts on June 10th, 2021, the rarest CrypoPunk 7523, *Covid Alien* sold for $11.754M USD; the official NFT of Kevin McCoy's 2014 "monetized graphic," Quantum, was sold for $1.472k USD. In total, nearly $17M USD was realized across the 27 listed artists [15].

Even before the introduction of a NFT-specific standard, ERC-721, though, Ethereum had become the hosting blockchain of choice due to its built-in scripting language, Solidity, used to implement automatic smart contracts, and the ERC-20 standard which facilitated tracking the creation and transfer of tokens. The November 2017 introduction of CryptoKitties (Dapper Labs), a video game centered upon the trading and breeding of virtual avatar cats, however, solidified this role. The viral popularity of CryptoKitties necessitated an overhaul of the Ethereum blockchain to manage network congestion and the associated increase in transaction fees: in December 2017 it was reported that they represented approximately 25% of all Ethereum transactions [16]. To address this increased network load, changes to the Gas limit, or maximum amount of gas (and energy) a user is willing to spend to complete a transaction, were made to allow more (and therefore, faster) transactions per block (minimum Gas per transaction currently set to 21,000 units). ERC-721 NFT protocol was published January 24th, 2018 with CryptoKitties the first NFT platform to utilize it [17]. Further details on the operation of Ethereum are provided in Section IV.

Although CryptoKitties places value on 'rarity,' as with the intrinsic value of their first generation Kitties beginning with Genesis, or their Diamond line of Kitties with 'Mewtations,' there has always been a focus on increasing market share via crossbreeding the Kitties. In September 2018 it was reported that over 1 million CryptoKitties had been bred; as of 2021 Q3 there are approximately 2 million, with $7.27 M USD worth transacted over September 2-3, 2021 alone [18]. In contrast, a collectible such as CryptoPunks, which has a finite 10,000 in existence, relies upon a scarcity mechanism which has seen a turnover of approximately 14,000 sales in the past year [19], albeit for typically higher prices per *Punk* than are realized for most CryptoKitties [17]. To support this market growth, and increase Kitty functionality, such as animation, Dapper Labs has indicated that they intend to migrate CryptoKitties to their own blockchain, Flow [17].

Nevertheless, NFTs have only ever been representative of an object, not the object itself, even in its digital form. The NFT is the pointer to the object, often via a cryptographic hash link to a decentralized file storage system such as the Interplanetary File System (IPFS) link. Only the record of the transaction conferring or transferring ownership is registered

TABLE II
COMPARISON OF POPULAR NFT PLATFORMS

Platform	Nifty Gateway [21]	OpenSea [22]	SuperRare [23]
Blockchain	Ethereum (ERC-721)	Ethereum (ERC-721, -1155)	Ethereum (ERC-721)
Currency	Credit Card, some pre-paid ETH	ETH, WETH, DAI, USDC	ETH
Juried	Invitation after application	No, but referral program gives 2.5% to referrer	Invitation after application
Fees	20% of sale + 30¢ to platform	No upfront fees (lazy minting), 2.5% of sale to platform	3% minting fee, 15% of sale to platform
ARR	creator select 5-50%, 5% + 30¢ to platform	up to 10%, 2.5% to platform	10% to creator, 3% to platform
Wallet	MetaMask	MetaMask, WalletConnect	MetaMask, Formatic
Type of Sales	Auctions, Silent Auctions, Fixed Price, Open/Limited Editions	Auctions, Dutch Auctions, Fixed Price, Open Offer	Auctions, Fixed Price
Notable Sales	Grimes *War Nymph Vol.1*, $5.8M USD	CryptoPunk #7804, last sale: $7.5 M USD	TIME Magazine *The Future of Business May 10/17, 2021* cover art by Beeple, primary: $326k USD; secondary: $2.6 M USD

on the blockchain. Consequently, NFT 'broken links' are a well-known issue, about which more will be discussed below.

In the case of digital art, the NFT purchase provides basic usage rights, such as posting online, setting as user profile, backed by the "bragging rights" [20] of the provenance of a blockchain entry. A summary comparison of three of the most popular NFT selling platforms is provided in Table II.

IV. HOW DO NFTS WORK?

Although the concept of unique, non-fungible tokens utilizing Ethereum's smart contract structure has been explored from the early days of Ethereum, as per the eponymous CryptoPunks and first generation CryptoKitties, NFTs in their current context were first defined in the Ethereum Improvement Proposal (EIP) Ethereum Request for Comment (ERC)-721 Non-Fungible Token Standard, published January 24th, 2018. As stated in the proposal, the motivation for creating this standard was that the existing token standard, ERC-20, "is insufficient for tracking NFTs because each asset is distinct (non-fungible) whereas each quantity of tokens is identical (fungible) [4]." The intention with ERC-721 is to provide a standard Application Programming Interface (API) for managing NFTs within the existing Ethereum smart contract structure, whether they be existing virtual collectibles, physical property, or negative value assets such as loans. A comparison table of token standards, ERC-20 [24], ERC-721 [4], ERC-998 [25], ERC-1155 [26], and later standards for dealing with multiple fungible and non-fungible tokens, is provided in Table III.

Once an NFT has been minted (created) on e.g., Ethereum, a process that involves a gas transaction fee, a record of its creation is stored in an Ethereum hash of the smart contract which includes the owner's wallet address and a link to the NFT. NFTs are always stored off-chain due to size and cost constraints resulting in this link providing the only connection to the created object. As a result, although the record of the NFT is secure, the NFT itself is dependent upon the continuing existence of the webhost. A consequence is the loss

of neutrality and decentralization inherent to the blockchain ethos, since these platforms come under the control of the elite few. Another consequence is fragility in the 'archival bond' [27], the unique link between the transaction record on chain (i.e., the ledger record) and the digital asset to which it refers. Website *checkmynft.com* [28] allows users to check whether their NFTs are still accessible or if they have been lost to a broken link. This so-called 'broken link problem' is discussed in further detail in Section VII-F.

V. HOW TO BUY AN NFT

As the first blockchain to provide built-in smart contract functionality, as previously described, Ethereum is the preferred platform for the buying and selling of NFTs [29]. Although other blockchains can implement standards to support the mining and trading of unique crypto tokens, as with the early Bitcoin Colored Coin experiment [30], or TRON-specific NFT standards [6], Ethereum's early advantage has effectively resulted in a technical lock-in. The largest and most established NFT trading platforms: Nifty Gateway [21], OpenSea [22], and SuperRare [23], as examples, are all based on the Ethereum blockchain and as such require payment, both for purchase and transactional gas, in ETH. Thus, minting NFTs does not come without costs for GLAM institutions. A further comparison of these platforms is provided in Table II.

Although traditional art auction houses such as Christie's [31] and Sotheby's [32] have facilitated payment of NFTs using either traditional fiat currencies (such as GBP or USD), in addition to more established cryptocurrencies (BTC or ETH), all NFT platforms require an Ethereum-compatible cryptowallet to host the digital NFT [21] - [23] [31] [32]. The most popular, MetaMask [33], a component of the Consensys toolkit that offers Ethereum development platform Truffle Suite, is suitable for both fungible and non-fungible tokens. Other NFT specific wallets such as WalletConnect [34] or Formatic [35] may also be used depending upon the platform requirements, as summarized in Table II. In the case of Christie's record breaking Beeple sale, *Everydays*

was purchased for 42,329.453 ETH ($69.3M USD) by crypto-billionaire 'Metakovan,' later revealed to be Vignesh Sundaresan, founder of MetaPurse, an NFT collection fund [36].

Although each NFT hosting platform has its own procedure for purchasing an NFT, the methodology can be generalized, as described in Algorithm 1. *OpenSea.io* [22] is chosen as the most popular platform for posting all types of NFTs (not just artwork) without requiring an invitation or adjudication process.

Algorithm 1 How to Purchase an NFT (on OpenSea)

Create (MetaMask) wallet to interact with Ethereum blockchain.

Download browser extension and pin to browser for easy access.

Remember (and keep secret) the private key phrase

Link MetaMask wallet to bank account, ApplePay, or PayPal to access fiat currency

Visit Ethereum exchange within wallet by selecting 'Add Funds' to purchase ETH.

The most popular exchange is Coinbase: Gemini, Bitstamp, and Kraken exchanges are also available in North America. ETH is required for:

[1] Purchasing NFTs and other Ethereum tokens

[2] Paying the network transaction fee, gas, to mint and list an NFT.

Visit NFT hosting website, such as OpenSea.io, and link Ethereum wallet to a new account

This process is automatic if wallet extension is pinned to the browser.

Browser the Marketplace to view current (and historic) NFT auctions. Bid on or 'buy now' an NFT.

if Bid is successful **then**

    Pay NFT auction price and variable transactional gas cost for using the Ethereum blockchain.

    Record the completion of the auction and the transfer of the NFT to the winning bidder's wallet address.

    if Payment is successful **then**

        Transaction is recorded on Ethereum blockchain.

        Ownership of an NFT typically conveys usage rights.

        Original artist retains copyright and a stake (10%) in the subsequent resale of their NFT.

    else

        Transfer is cancelled if insufficient ETH in the wallet.

    end if

end if

VI. HOW TO CREATE (AND SELL) AN NFT

The minting of NFTs is a similar process to their purchase, as outlined in Section V. As described in the main NFT standard, ERC-721, minting (creation) and burning (destruction) of an NFT is outside the scope of the standard and to be handled by the hosting platform. Therefore the following methodology has been generalized, with particular reference to *OpenSea.io*, the largest non-adjudicated, open NFT sale platform [37].

Algorithm 2 How to Mint an NFT (on OpenSea)

Create a (MetaMask) wallet to interact with the Ethereum Blockchain

Download and pin wallet browser extension for easy access

Remember and keep secret the 256-bit private key seed phrase composed of 12 random words

Link MetaMask wallet to bank account, ApplePay, or PayPal to access fiat currency

Visit Ethereum exchange within wallet by selecting 'Add Funds' to purchase ETH. The most popular exchange is Coinbase, but Gemini, Bitstamp, and Kraken exchanges are also available in North America. ETH is required for both purchasing NFTs and other Ethereum tokens, and for paying the network transaction fee, gas, to mint and list an NFT.

Visit an NFT hosting website, such as OpenSea, and select 'Create.' Will be prompted to link Ethereum wallet to create an account, unless it has been pinned to the browser in which case sign in is automatic.

Create a 'New Collection.' It is free to create an NFT. A user is only charged if the NFT is transferred or put up for sale. Creation policies such as by invitation (EG) or adjudication (EG) vary for different NFT hosting platforms.

Create a new item within the collection subject to size constraints. NFT may be wholly visual (2D or '3D'), animated, with sound, or reference a physical object. Provide URL or IPFS link.

Viewable only: free

Saleable: costs gas to upload auction to Ethereum. Gas is a variable cost based upon current Ethereum network congestion. Two transactions are required to create a saleable NFT, typically in the range of $50-$100 USD as of August 2021:

Mint a token mapped to uploaded file to act as a unique cryptographic signature. Adding the NFT to Ethereum record requires transactional gas

Set the reserve price and run auction: automatically generates smart contract code.

Transfer to another address without sale: costs (less) gas to record transfer on Ethereum

Auction process varies. Purchaser pays gas fee for NFT transfer.

Most platforms have a built-in platform maintenance and artist resale right (ARR) to their smart contracts, as outlined in Table II.

Nevertheless, anything that is created can be stolen and the impetus to do so increases with the object's value. The following Section VII outlines the main mechanisms by which an NFT can be stolen, or lost.

TABLE III: Ethereum Standards Comparison

Name	ERC-20 Token Standard	ERC-721 Non Fungible Token (NFT) Standard	ERC-998 Composable NFT Standard	ERC-1155 Multi Token Standard
Created	19 November 2015	24 January 2018	7 July 2018	17 June 2018
Motivation	-provides a standard interface which allows fungible tokens to be re-used by different applications on Ethereum	-inspired by ERC-20 standard -provides a standard interface which allows unique tokens (NFTs) to be identified and re-used by different applications on Ethereum -includes ability for smart contract to include arbitrarily large numbers of NFTs	-extends ERC-721 to enable such tokens to own other ERC-721 or ERC-20 tokens -extends ERC-20 standard to enable such tokens to be owned by ERC-721 tokens -top-down composable contract stores and tracks child token for each token -bottom-up composable contract stores and tracks parent token for each tokens	-allows smart contracts to manage multiple token types, fungible, non-fungible, and other configurations (i.e. semi-fungible) -can transfer tokens in batches to save on transaction costs (Gas) -ERC-20 and other standards require a separate smart contract for different token types, which leads to redundant byte code on Ethereum
Identifier	-function 'name' returns string of token name -optional function 'symbol' returns string of token symbol	-unique uint256 ID within Smart Contract that will not change for life of the contract -(contract address, uint256 token ID) globally unique and fully qualified ID on Ethereum	-handled by ERC-721 or ERC-20 standards, depending upon token type	-_id uint256 -top 128 bits may represent base token ID -bottom 128 bits may represent index of NFT ID to make unique
Transfer Mechanism	transfer: -transfer _value number of tokens to wallet address _to transferFrom: -transfer _value number of tokens from address _from tp address _to -both functions must trigger Transfer event	safeTransferFrom: -owner of NFT -approved address of NFT -authorized operator of owner of NFT	-owner: rootOwner at top of tree of composables and ERC721 tokens -transfer regular ERC-721 to NFTs: use top-down interface -transfer NFTs to regular ERC-721: use bottom-up interface	-_id argument indicates specific token type -supports non-batch transfer (eg. 1 token use case)
Privacy	—	-cannot be attained because attacker can call ownerOf for every possible tokenID -only possible if NFTs were not enumerated (eg. CryptoPunks)	-handled by ERC-721 or ERC-20 standards, depending upon token type	-standard guarantees that event logs emitted by smart contract will provide sufficient data to create a record of the token balance resulting in indexed and categorized searches of every ERC-1155 token in the contract

Name	ERC-20 Token Standard	ERC-721 Non Fungible Token (NFT) Standard	ERC-998 Composable NFT Standard	ERC-1155 Multi Token Standard
Interface	-is itself a standard interface for re-using fungible tokens on Ethereum	-requires ERC-165 *Standard Interface Detection* -wallet/broker/auction must implement wallet interface to accept safe transfer	-depending upon smart contract type, for a particular token, use: -ERC998ERC721 TopDown -ERC998ERC20 Top Down -ERC998ERC721 BottomUp -ERC998ERC20 BottomUp	-requires ERC-165 interface
Mint/Burn	-smart contracts that create new tokens should trigger a Transfer event with _from address set to 0x0	-'minting' - create -'burning' - destroy -not included in specification, must be implemented by NFT hosting platform	-handled by ERC-721 or ERC-20 standards, depending upon token type	-implemented as specialized transfers that must follow ERC-1155 rules for *safeTransferFrom* or *safeBatchTransferFrom* functions
Metadata	–	-optional Enumeration Extension -must provide 'name' and 'symbol,' but this can be an empty string (only available from web3) -optional - publish full list of NFTs and make them discoverable - useful for record keeping provenance	-handled by ERC-721 or ERC-20 standards, depending upon token type	-must specify hex ID if string id exists in Uniform Resource Identifier (URI) -optional extension *ERC1155Metadata_URI* allows ID substitution by clients
Backwards Compatibility	-developer should strive to make new smart contracts backwards compatible with older smart contracts but not enforceable	-CryptoKitties - yes -CryptoPunks - somewhat, but instead of being enumerated, each ID is called a 'punk' -Curio Cards and Rare Pepes - not distinguishable assets (NFTs), but rather a collection of individual fungible ERC-20 tokens, each tracked by smart contracts. Considered "limited edition, collectible tokens."	-compatible with ERC-20, ERC-721	-compatible with ERC-721 standard

VII. NFT Issues of Concern to GLAMs

Preserving and, subsequently, determining the authenticity of assets in their care and custody are primary concerns of all GLAM institutions, albeit approaches vary. In art, for example, authenticity has traditionally been determined by a combination of its provenance chain, the record of ownership beginning with the artist, and expert opinion on style and the history of the artist. In France, the *droit moral* allows the beneficiaries of an artist's estate to determine whether an artwork is authentic [38]. While legally this designation only applies in France, in practice, reputable art sellers located elsewhere would not consider an artwork without it. Some artists develop a *catalogue raisonné*, or complete record of their official works. However, many such records, if they exist, are expensive and difficult to access, are incomplete, or developed posthumously [39].

Where provenance records are weak or missing, scientific tests including x-ray (to determine if there is an underpainting), spectroscopy (to determine the chemical composition of materials to compare with an artist's palette or materials available at the time and location), and dendrochronological tree ring dating of wooden boards or carvings (to determine year and locale) can be used to aid the expert [40]. Therefore, in this context, provenance chains are often easier to forge than the artwork.

In archives, longer-term preservation of the authenticity of digital records also rests upon documenting their provenance - "the relationships between records and the organizations or individuals that created, accumulated and/or maintained and used them in the conduct of personal or corporate activity" [41] - and, ideally, establishing and documenting the records' chain of preservation - "a system of controls that extends over the entire lifecycle of records in order to ensure their identity and integrity over time" [42]. These objectives are primarily achieved through archival processes of arrangement and description and processes of digital records preservation as, e.g., outlined in ISO Standard 14721 [43].

Subsequent processes of authenticating records involve the gathering and evaluation of internal and external documentary evidence that a document is genuine and free from tampering. Archival diplomatics holds that records must have several elements necessary to instantiate their evidentiary quality. These are: medium, i.e., the physical carrier of the message; physical and intellectual form, being the rules of representation that allow for communication of records' evidentiary content; the content itself, i.e., the message that the record is intended to convey; action i.e., action or event that originates the record, as an exercise of the will of the record's author; persons, i.e., the entities acting by means of the record (e.g., the author, writer and addressee); an 'archival bond', i.e., the relationship linking each record to its originating action and to other records associated with the same action; and context, i.e., traditionally, the juridical, administrative, procedural, documentary, and technological context in which the record is created [44].

The use of a decentralized ledger provides the opportunity for a tamper-resistant provenance record. Nevertheless, as described in Section II, because NFTs are stored off chain and rely on startup web-platforms or Interplanetary File System (IPFS) seeding to host their works, there are issues with ensuring their long-term authenticity. Many elements necessary for later authentication can be missing from ledger records and associated documentation generated and retained in blockchain and distributed ledger systems supporting NFTs. Moreover, as these systems consist of many components with complex interdependencies, and are not stable, essential elements to establish the identity and integrity of all interconnected components are often absent (e.g., as in the case of the 'broken link' problem described in Section VII-F.)

A. The Media Was Stolen Before it Was Minted into an NFT

The great promise of NFTs, and, more broadly, blockchain, is their ability to track ownership, or the provenance, of unique tokens on a so-called immutable decentralized ledger. However, many platforms do not require the verification of users to prove that they are the rightful owners of the works they are minting into NFTs. Comically this has been leveraged to prove a point, as when Terence Eden of the Open Standards for the UK Government Digital Service (GDS) claimed 'ownership' of the Mona Lisa on Verisart's BTC-based art provenance tracking tool after providing only an email address and a photograph of the Mona Lisa from Wikipedia as 'proof' [45]. This issue, however, has also been experienced by contemporary artists who reportedly have also had their original works minted into NFTs without their consent [46]. Given the anonymous nature of much of blockchain culture, this issue is most pronounced amongst smaller or emerging artists and creators: the prominence of flagship sales such as Canadian musician Grimes' NFT sold on Nifty Gateway [21], or those sold at traditional auction houses such as Christie's [31] and Sotheby's [32], provide better confirmation of an NFT's authenticity, as does their traditional provenance tracking research.

B. NFTs and IP

Another grey-area is the legality of NFTs in relation to intellectual property (IP), specifically copyright. When a NFT is purchased, copyright is still retained by the original minter: the new owner has the right to display and sell the NFT, albeit under a platform stipulated ARR percentage being paid to the artist (further details provided in Table II). Furthermore, by definition, NFTs are 'memetic' and self-referential. Until 2020 most NFTs were too niche and not high enough value to generate dedicated copyright policy, in addition to being created by mostly anonymous artists. Most NFT platforms (OpenSea [22], SuperRare [23]) make some mention of copyright, explaining the role of *fair use* to criticize, parody, or comment on existing works without the permission of the original copyright holder. However, it is noted that fair use is decided on a case by case basis and SuperRare, an adjudicated platform, explicitly does not allow for use of other's copyright [23].

Under Section 504 of the U.S. Copyright Act [47], a copyright infringement could cost between $750 to $3k USD if the infringer was unknowing (ie. inadvertently purchased an artwork that used someone else's copyright), and up to $150k USD if the infringement is intentional, (i.e. copying someone else's work). As an example of the complexities of copyright in the world of NFTs, in August 2021, a 12 year old boy became a sensation for his *Weird Whales* NFT series still trading on OpenSea, total volume sold as of October 2021 sold 1.8 ETH (approximately $7.5 M USD) [48]. However, it became apparent that the 'Whales' were based upon publicly available images and owners of the NFTs began to sell them at a loss. The copyright issue was never directly addressed, but the concern that there may have been a copyright infringement was enough to stop the run [49]. Now that the NFT sector, as of 2021 Q3, is valued at over $9B USD [50] and significant revenue has been raised by the minting and sale of ubiquitous and freely shared memes such as Nyan Cat ($590k USD/ 300 ETH, February 19, 2021 [51]) and Disaster Girl ($500k on May 1, 2021 [52]), NFT copyright claims will take on a new significance. Copyright uncertainties, already a challenge for most GLAM institutions who often hold many 'orphaned' works, will not be helped by introduction of NFTs into their holdings. As usual, the written law lags behind technological applications.

C. Legitimate Auctions?

As with all e-commerce, whether a sale is legitimate or a scam can be called into question. Furthermore, as notably experienced with e-Bay and Ticketmaster, there is the risk of fake accounts artificially driving up prices. Although most NFT platforms have some consumer protection policies in place, as with Nifty Gateway's introduction of two-factor authentication (2FA) via partner company, Gemini [21], or OpenSea's [22] ability to lock down accounts and only re-instate with a sworn affidavit from a notary public, the anonymous nature of such platforms creates difficulty in tracing bad actors: the prevailing message is *caveat emptor*.

D. Private Key is Compromised

Once an NFT has been minted and sold, the next opportunity for stealing it is if the private key of the owner's cryptocurrency wallet is compromised. Cryptocurrency wallets operate via a handshake mechanism whereby the wallet address and its associated public key are published on the blockchain: Ethereum includes this information in the associated smart contract [24]. The associated private key, however, must be kept secret by the owner. If revealed, whether by inadvertence or force, then the wallet is no longer secure and all assets housed in the wallet may be extracted by whomever holds the private key. In the case of fungible cryptocurrencies, there is minimal recourse for regaining stolen items as the interchangeability of the tokens ensures that the cryptocurrencies may be effectively 'laundered' by transferring to other wallets. A notable exception was the recovery of 64 BTC (approximately $2.3M USD) of Colonial Pipeline's ransom to DarkSide hacking group on May 27, 2021, an extraction that required the FBI to trace the stolen funds [53]: not a practicable solution for recovering most thefts.

In the case of NFTs, though, their uniqueness may provide some ability to track and return the asset to the rightful owner. Nevertheless, the traditional art market has always thrived upon the ability to trade in stolen art and this feature is unlikely to change with a new medium [54]. Furthermore, in many cases the transfers may be considered 'legal' within the rules set out by the blockchain [55]. For this reason, many government organizations, such as the UK's Financial Conduct Authority (FCA), have banned crypto derivatives and exchange traded notes (ETNs) as of October 6, 2020 "that reference certain types of crypto assets to retail consumers," to protect consumers, stating that consumers who do use crypto derivatives cannot expect protection from either price volatility or lost or stolen assets [56].

E. Private Key is Lost

An NFT may also be lost if the wallet owner loses the private key. Most NFT platforms, such as CryptoKitties [17], warn their users that the NFTs, as with all wallet contents, are unrecoverable if the user becomes locked out of the wallet, an issue that has become well documented: in this instance the wallet contents are completely lost and out of circulation.

Notably, in January 2021, a Welsh IT engineer became infamous for attempting to search a local garbage dump for a hard drive he mistakenly threw away in 2013 which allegedly held the private key for 7,500 BTC. At the time the hard drive was lost, the BTC would have been worth approximately $4.5M USD (approximately $600 USD/BTC). When the story broke, the BTC stash had increased in value to approximately $280M USD (approximately $37k USD/BTC); as of October 2021, the stash is now worth approximately $475M USD (approximately $63k USD/BTC). So far, the local council responsible for the dump has declined to allow him to search for the hard drive [57].

Research suggests that up to 20% of BTC is permanently out of circulation due to lost private keys [58]. Other noteworthy examples include a Ukrainian politician who inadvertently deleted an encrypted file containing his private key to 400 BTC (worth approximately $25M USD in October 2021) to free up space on his computer [59], and a German engineer based in San Francisco who forgot the password to his encrypted Iron Key hard drive [60]. With only two attempts of 10 remaining before the contents are destroyed, he stood to lose 7002 BTC (approximately $443M USD in October 2021). Ultimately, he was unable to recover the funds before he ran out of attempts.

Most infamously, however, is Canadian Gerald Cotten, CEO and founder of QuadrigaCX, a cryptocurrency exchange later found to be a Ponzi scheme by the Ontario Securities Commission (OSC) in 2020 [61]. Cotten is accused of faking his own death during a trip to India in 2018 to abscond with the private key to 11,500 of QuadrigaCX's cryptocurrency investments including 26,500 BTC (worth approximately $1.7B USD in October 2021), 11,000 BTC Cash (trading at approximately

$755 in October 2021, worth $8.3M USD), 200,000 Litecoin (trading at approximately $187 USD in October 2021, worth $37.4M USD), and 430,000 ETH (trading at approximately $3,800 USD in October 2021, worth $1.64B USD). His widow claims that only he had knowledge of the private key: the funds have never been recovered.

F. The Broken Link Problem

Beyond user error, though, the most significant way an NFT can be lost is an increasing issue that is intrinsic to NFT system design, so called the 'broken link problem.' NFTs have only been widely in circulation since 2017 and already there are many that have become 'lost' [62]. As explained by Anil Dash, one of two creators of proto-NFTs, this is a fundamental flaw with existing NFT representations on blockchains [10]. As an NFT file is typically too large, and therefore the gas cost to store on chain too expensive, a hash of the link to the NFT is provided in the smart contract instead. However, these off chain storage solutions (i.e., external websites) are not subject to maintaining an immutable ledger: merely not renewing the web domain is enough for the NFT link to 'break' and point to nowhere. As previously mentioned, website *checkmynft.com* allows users to determine whether their links have become defunct [28].

A major argument in favour of blockchains as records sytems is that because every transaction is saved to the blockchain, all records, including NFTs, should be recoverable, even if the hosting platform goes offline. In practice, however, these NFTs are not renderable and are considered 'lost.' Although it may be possible for the owner to download a local copy of an NFT for their own enjoyment, this would not be considered the authoritative version, subject to resale rights. Unfortunately, until NFT platforms are secured to exist in perpetuity, similar to blockchains themselves, there is not a tractable method of avoiding the broken link problem for digital-only NFTs.

Links also may be broken because the NFT is copied, as with high value memes such as Nyan Cat [51] or Disaster Girl [52] which themselves are digital copies or editions. In such cases, it becomes difficult to determine which copy is the original NFT and reassert ownership. While some NFT platforms attempt to address this issue by hosting their NFTs using interplanetary file system (IPFS), a peer-to-peer (P2P) web-based file system which helps to ensure that files are distributed across many hosts, this is not a universal practice [62]. Further, IPFS relies on the popularity of a seeded file to continue access: if an NFT is no longer of interest to this community, it, too, suffers from the broken link problem and the file is effectively lost.

As described in Section IV, some crypt-millionaires and - billionaires have purchased controlling shares in NFT hosting platforms to ensure ongoing access to their purchased NFTs, a solution that presents its own implications for blockchain neutrality and certainly out of reach for most small-scale and under-resourced GLAM institutions, at least if they work alone.

G. Are NFTs Bad for the Environment?

Concurrent to the rise in popularity of cryptocurrency has been an increased awakening to the 'climate crisis' [63]. In spite of government pledges to begin significantly reducing greenhouse gas (GHG) emissions beginning in British Columbia, Canada's 2007 Throne Speech, and reaffirmed internationally with the 2012 Paris Agreement and most recently, Glasgow's November 2021 Cop26 UN Climate Change Conference of the Parties, little improvement has been made [64]. As with the Extinction Rebellion, much emphasis has been placed on the individual to make lifestyle changes to retard the effects of climate change due to excess consumerism and the associated energy consumption, typically from GHG-emitting fossil fuels. This energy, however, would perhaps be better deployed educating individuals to become empowered lobbyists: a 2017 Carbon Disclosure Project (CDP) *Carbon Majors Report* revealed that 100 companies, mainly related to fossil fuel energy sources, represented 71% of all GHG emissions between 1988 and 2015, with 32% of all emissions linked to public investor owned companies [65]. By comparison, the entire nation of Canada accounts for 1.6% of global emissions, well within a conservative $\pm 5\%$ margin of error [66]. Therefore, while important to develop informed consumers, the greatest emphasis should be placed upon changing the structure by pressuring governments to regulate the highest emitting companies and industries, particularly as, in the case of industries such as the garment industry, high GHG emissions are also accompanied by human rights violations [67].

A sector that requires more clarity, however, is the digital sector. The massive server energy consumption represented by this sector is further exacerbated for cryptocurrencies, and by extension, NFTs. The Proof of Work (PoW) consensus algorithm used in public, permissionless blockchains such as Ethereum is particularly well-known as an energy hog, with many researchers pointing out that it regularly consumes the energy equivalent of a small nation just to confirm a few blockchain transactions [68].

Proof of Stake (PoS) consensus, on the other hand, which instead relies upon validators to maintain the cryptocurrency, and to which the Ethereum blockchain plans to transition, is considered to be a more environmentally conscious option. PoS requires crypto-owners to 'stake' their tokens as collateral against the stability of the cryptocurrency and rewards them with control over new mining of crypto-tokens in proportion to the amount they staked. Over time, these stakes can grow via network fees from other users writing transactions to a block under the crypto-owner's control, newly minted coins, or other reward mechanisms such as uncle blocks. The high energy consumption associated with validating cryptographic puzzles, as reported by Cambridge's BTC Electricity Consumption Index, is no longer required [69].

Although PoS in legacy blockchains still favours early adopters who have already built up a substantial stake when the cryptocurrency was trading a lower value, the required

stake, 32 ETH (approximately $90k USD) is considered to facilitate a more democratized approach to DeFi than the 'winner takes all' competitive model in PoW systems [70], albeit at a lower system fault tolerance and with reduced system security (by the Byzantine model, 33% of malicious blocks can be supported versus Bitcoin's 50%) [71].

VIII. CONCLUSION: THE FUTURE OF NFTS

GLAM institutions have always experienced budgetary pressures, and this has only worsened with the global pandemic. With the rise of NFTs, they now have a tool that could enable them to rethink their financial models. Monetization using blockchains and NFTs has the potential to enable the circulation of a work from a collection while also generating income from it. Funds have already been raised for the Uffizi, the Hermitage, the Whitworth and the British Museum using NFTs [72]. Whether this policy is appropriate or not, or should become part of the long-term strategy of GLAM institutions, it seems clear that NFTs are likely to be new types of digital objects that will form part of the future holdings of GLAM institutions. It is for this reason, more than the opportunity to generate revenue, that it is incumbent upon GLAMs to familiarize themselves with what NFTs are, how they work, and the open challenges associated with them. This paper has presented a first survey of the topic from a cultural heritage perspective; however, we recognize that much more research on NFTs and their use and preservation by GLAM institutions is needed.

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REFERENCES

[1] BM NFTs: M. Cole. "103 Unpublished Hokusai Drawings Featured in New Exhibit and 200 NFTs of His Works Will Be Sold." My Modern Met. (Oct. 7, 2021) [Online] https://mymodernmet.com/british-museum-hokusai-exhibition-and-nft-sales/#: :text=The%20British%20Museum%20has%20partnered,or%20at%20a%20fixed%20price (accessed Oct. 28, 2021).

[2] V. L. Lemieux, "A typology of blockchain recordkeeping solutions and some reflections on their implications for the future of archival preservation," 2017 IEEE International Conference on Big Data (Big Data), 2017, pp. 2271-2278, doi: 10.1109/BigData.2017.8258180.

[3] "Institute of Contemporary Art, Miami Acquires CryptoPunks NFT Through Major Gift from Trustee Eduardo Burillo." Resnicow and Associates. (Jul. 6, 2021). [Online] https://newsroom.resnicow.com/institute-of-contemporary-art-miami-acquires-cryptopunks-nft-through-major-gift-from-trustee-eduardo-burillo/ (accessed Oct. 28, 2021).

[4] *EIP-721: Non-Fungible Token Standard*, W. Entriken, D. Shirley, J. Evans, N. Sachs, Jan. 24, 2018. [Online]]https://eips.ethereum.org/EIPS/eip-721

[5] "NFTfi: The marketplace for NFT collateralised loans." [Online] https://www.nftfi.com/ (accessed Oct. 15, 2021).

[6] *TRC-721 Standard*, Apr. 2021. [Online] https://developers.tron.network/docs/trc-721

[7] "Andy Warhol's 14 Small Electric Chairs To Be Sold in Blockchain Art Auction." Maecenas. (Jun. 6, 2018). [Online] https://blog.maecenas.co/andy-warhols-14-small-electric-chairs-to-be-sold-in-blockchain-art-auction/ (accessed Jul. 5, 2021).

[8] "Online Auction 20447: Beeple, The First 5000 Days." Christie's. (Mar. 12, 2021). [Online] https://onlineonly.christies.com/s/beeple-first-5000-days/beeple-b-1981-1/112924 (accessed Jul. 5, 2021).

[9] "Buy, sell and mint fractions of NFTs." [Online] https://fractional.art/ (accessed Oct. 15, 2021)

[10] A. Dash. "NFTs Weren't Supposed to End Like This." Atlantic. (Apr. 2, 2021) [Online] https://www.theatlantic.com/ideas/archive/2021/04/nfts-werent-supposed-end-like/618488/ (accessed Jul. 5, 2021).

[11] Rare Pepes. [Online] https://rarepepes.com/ (accessed Jul. 13, 2021).

[12] Curio Cards. [Online] https://curio.cards/ (accessed Jul. 13, 2021).

[13] C. Williams. "Rare Homer Simpson Pepe NFT Sells for $320,000." Crypto Briefing. (Mar. 2, 2021) [Online] https://cryptobriefing.com/rare-homer-simpson-pepe-nft-sells-320000/ (accessed Jul. 13, 2021).

[14] CryptoPunks. [Online] https://www.larvalabs.com/cryptopunks (accessed Jul. 13, 2021).

[15] "Natively Digital: A Curated NFT Sale." Sotheby's (Jun. 10, 2021). [Online] https://www.sothebys.com/en/buy/auction/2021/natively-digital-a-curated-nft-sale-2 (accessed Jul. 22, 2021).

[16] B. Garner. "What is CryptoKitties? A Beginner's Guide on the Blockchain Collectible Cats." Coin Central. (Apr. 10, 2018). [Online] https://coincentral.com/cryptokitties-beginners-guide/ (accessed May 13, 2021).

[17] CryptoKitties. [Online] https://www.cryptokitties.co/ (accessed May 13, 2021).

[18] "Is CryptoKitties the Next Breakout NFT Collectible? Trading Volume Data Indicates so." Crypto News. (Sep. 3, 2021). https://cryptonews.net/en/news/nft/1671931/ (accessed Oct. 7, 2021).

[19] R. Curry. "Why Are CryptoPunks So Expensive? The OGs of NFTs Gain Serious Value." Market Realist. (Aug. 6, 2021). [Online] https://marketrealist.com/p/why-are-cryptopunks-so-expensive/ (accessed Oct. 7, 2021).

[20] G. Ruiz. "Buyer Beware: NFTs and Intellectual Property Rights." Medium. (Mar. 8, 2021). [Online] https://georgeruiz.medium.com/buyer-beware-nfts-and-intellectual-property-rights-9f45b3812e28 (accessed Oct. 7, 2021).

[21] Nifty Gateway. [Online] https://niftygateway.com/ (accessed Oct. 7, 2021).

[22] OpenSea. [Online] https://opensea.io/ (accessed Oct. 7, 2021).

[23] SuperRare. [Online] https://superrare.com/ (accessed Aug. 9, 2021).

[24] *EIP-20: Token Standard*, F. Vogelsteller, V. Buterin. , Nov. 19, 2015. [Online] https://eips.ethereum.org/EIPS/eip-20

[25] *EIP-998: ERC-998 Composable Non-Fungible Token Standard*, M. Lockyer, N. Mudge, J. Schalm, Jul. 7, 2018. [Online] https://eips.ethereum.org/EIPS/eip-998

[26] *EIP-1155: Multi Token Standard* W. Radomski, A. Cooke, P. Castonguay, J. Therien, E. Binet, and R. Sandford, Jun. 17, 2018. [Online] https://eips.ethereum.org/EIPS/eip-1155

[27] L. Duranti. (1997). "The archival bond," *Archives and Museum Informatics*, vol. 11, no. 3, pp. 213-218, Sep. 1997.

[28] Check My NFT. [Online] https://checkmynft.com/ (accessed Aug. 9, 2021).

[29] "Market Overview." Nonfungible. [Online] https://nonfungible.com/market/history (accessed Oct. 28, 2021).

[30] "Colored Coins." Bitcoin Wiki. (Jul. 9, 2018). [Online] https://en.bitcoinwiki.org/wiki/Colored_Coins (accessed Mar. 13, 2021).

[31] "Christie's Encrypted: Welcome to the Future - Digital NFTs" [Online] https://www.christies.com/auctions/christies-encrypted (accessed Oct. 4, 2021).

[32] "Bidder's Guide: NFTs and Cryptocurrency at Sotheby's." Sotheby's. (Jun. 10, 2021) [Online] https://www.sothebys.com/en/buy-sell/cryptocurrency-faq (accessed Oct. 4, 2021).

[33] "A crypto wallet & gateway to blockchain apps." MetaMask. [Online] https://metamask.io (accessed May 13, 2021).

[34] WalletConnect. [Online] https://sync-mywallets.com/ (accessed Oct. 8, 2021).

[35] Fortmatic. [Online] https://fortmatic.com/ (accessed Oct. 8, 2021).

[36] R. Frank. "Crypto investor who bought Beeple's NFT for $69 million says he would have paid even more." CNBC. (Mar. 30, 2021). [Online] https://www.cnbc.com/2021/03/30/vignesh-sundaresan-known-as-metakovan-on-paying-69-million-for-beeple-nft.html (accessed May 13, 2021).

[37] "OpenSea." DappRadar. [Online] https://dappradar.com/ethereum/ marketplaces/opensea (accessed Oct. 28, 2021).

EIP-998: ERC-998 Composable Non-Fungible Token Standard, M. Lockyer, N. Mudge, J. Schalm, Jul. 7, 2018. [Online] https://eips.ethereum.org/EIPS/eip-998

[38] "Ch. I: Moral Rights (Articles L121-1 to L121-9)," *Intellectual Property Code,* Jul. 3, 1992. [Online] https://www.legifrance.gouv.fr/codes/article_lc/LEGIARTI000006278891/

[39] Catalogue Raisonné Scholars Association. [Online] https://www.catalogueraisonne.org/ (accessed Jul. 12, 2021).

[40] "Provenance Guide." International Foundation for Art Research. [Online] https://www.ifar.org/Provenance_Guide.pdf (accessed Jul. 12, 2021).

[41] "Provenance." Interpares Trust. (2018) [Online] https://interparestrust.org/terminology/term/provenance

[42] "Preservation." Interpares Trust. (2018) [Online] https://interparestrust.org/terminology/term/preservation

[43] *Space data and information transfer systems — Open archival information system (OAIS) — Reference model,* ISO 14721:2012, 2018. [Online] https://www.iso.org/standard/57284.html

[44] L. Duranti & R. Preston. (2008). International research on permanent authentic records in electronic systems (InterPARES) 2: Experiential, interactive and dynamic records (pp. 34-35). Padua, Italy: CLEUP.

[45] W. Woo. "'Leonardo da Vinci' Puts Mona Lisa Painting on the Blockchain." Bitcoinist. (Jun. 14 2018). [Online] https://www.bitcoininsider.org/article/29846/leonardo-da-vinci-puts-mona-lisa-painting-blockchain (accessed May 13, 2021).

[46] J. Purtill. "Artists report discovering their work is being stolen and sold as NFTs." ABC Science. (Mar. 15, 2021). [Online] https://www.abc.net.au/news/science/2021-03-16/nfts-artists-report-their-work-is-being-stolen-and-sold/13249408 (accessed Aug. 9, 2021).

[47] "Title 17, Ch. 5: Copyright Infringement and Remedies," *Copyright Law of the United States*, Dec. 27, 2020. [Online] https://www.copyright.gov/title17/92chap5.html#504

[48] Weird Whales. [Online] https://weirdwhalesnft.com/ (accessed October 8, 2021).

[49] J. Schmalfeld. "Copyright violations could crash the NFT party." Yahoo Finance. (Aug. 4, 2021). [Online] https://finance.yahoo.com/news/copyright-violations-could-crash-nft-100000856.html (accessed October 15, 2021).

[50] "NFTs Overview." DappRadar [Online] https://dappradar.com/nft (accessed Oct. 28, 2021).

[51] "Nyan Cat NFT." Foundation. (Feb. 19, 2021). [Online] https://foundation.app/@NyanCat/ /219 (accessed May 13, 2021).

[52] "Disaster Girl NFT." Foundation. (Apr. 17, 2021). [Online] https://foundation.app/@DisasterGirl/ /25046 (accessed May 13, 2021).

[53] "Department of Justice Seizes $2.3 Million in Cryptocurrency Paid to the Ransomware Extortionists Darkside." U.S. Department of Justice, Office of Public Affairs. (Jun. 7, 2021). [Online] https://www.justice.gov/opa/pr/department-justice-seizes-23-million-cryptocurrency-paid-ransomware-extortionists-darkside (accessed Sep. 14, 2021).

[54] *Stolen Works of Art Database,* Interpol. [Online] https://www.interpol.int/Crimes/Cultural-heritage-crime/Stolen-Works-of-Art-Database (accessed Sep. 14, 2021).

[55] "History and Forks of Ethereum." Ethereum. https://ethereum.org/en/history/#dao-fork (accessed Sep. 14, 2021).

[56] "FCA bans the sale of crypto-derivatives to retail consumers." Financial Conduit Authority. (Oct. 6, 2020). [Online] https://www.fca.org.uk/news/press-releases/fca-bans-sale-crypto-derivatives-retail-consumers (accessed Sep. 14, 2021).

[57] T. Murray. "A man who says he threw away a hard drive loaded with 7,500 bitcoins in 2013 is offering his city $70 million to dig it up from the dump." Business Insider. (Jan. 16, 2021) [Online] https://www.businessinsider.com/man-offers-council-70-million-dig-up-bitcoin-hard-drive-2021-1 (accessed Oct. 4, 2021).

[58] B. Winck. "There's roughly $140 billion of inaccessible bitcoin right now - or 20% of the world's limited supply. Here's what could happen to it." Markets Insider. (Jan. 12, 2021). [Online] https://markets.businessinsider.com/news/currencies/bitcoin-price-btc-inaccessible-cryptocurrency-digital-currency-wallet-security-blockchain-2021-1 (accessed Oct. 4, 2021).

[59] S. Clement. "Ukrainian politician losses $25 million worth of Bitcoin after deleting private key." BTC Peers. (Apr. 15, 2021). [Online] https://btcpeers.com/ukrainian-politician-losses-25-million-worth-of-bitcoin-after-deleting-private-key/ (accessed Oct. 4, 2021).

[60] A. Akhtar. "A German programmer has 2 chances to correctly guess the password to his hard drive or he'll lose $220 million." Insider. (Jan. 12, 2021). [Online] https://www.businessinsider.com/programmer-locked-out-220-million-in-bitcoin-forgotten-password-2021-1 (accessed Oct. 4, 2021).

[61] "QuadrigaCX: A Review by Staff of the Ontario Securities Commission." Ontario Securites Commission, Apr. 14, 2020. [Online] https://www.osc.ca/quadrigacxreport/

[62] J. Kastrenakes. "Your million-dollar NFT can break tomorrow if you're not careful." The Verge. (Mar. 25, 2021). [Online] https://www.theverge.com/2021/3/25/22349242/nft-metadata-explained-art-crypto-urls-links-ipfs (accessed Sep. 14, 2021).

[63] "The Paris Agreement." United Nations Framework Convention on Climate Change. [Online] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed Sep. 14, 2021).

[64] "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change." The Intergovernmental Panel on Climate Change (IPCC). (Aug. 2021) [Online] https://www.ipcc.ch/report/ar6/wg1/

[65] P. Griffin. "The Carbon Majors Database: CDP Carbon Majors Report 2017." Climate Disclosure Project. (Jul. 2017). [Online] https://6fefcbb86e61af1b2fc4-c70d8ead6ced550b4d987d7c03fcdd1d.ssl.cf3.rackcdn.com/cms/reports/documents/000/002/327/original/Carbon-Majors-Report-2017.pdf?1501833772

[66] H. Ritchie and M. Roser. "CO_2 and Greenhouse Gas Emissions." Our World In Data. (2020) [Online] https://ourworldindata.org/co2/country/canada (accessed Sep. 14, 2021).

[67] Fashion Revolution. [Online] https://www.fashionrevolution.org/ (accessed Sep. 14, 2021).

[68] D. Das and A. Dutta. "Bitcoin's energy consumption: Is it the Achilles heel to miner's revenue?" Economics Letters, vol. 186, 2020. [Online] https://doi.org/10.1016/j.econlet.2019.108530

[69] "Cambridge Bitcoin Electricity Consumption Index." University of Cambridge, Judge Business School, Centre for Alterative Finance. [Online] https://cbeci.org/index (accessed Sep. 14, 2021).

[70] *EIP-3554: Difficulty Bomb Delay to December 2021,* J. Hancock, May 6, 2021. [Online] https://eips.ethereum.org/EIPS/eip-3554

[71] "Proof of Stake FAQs." Ethereum Wiki. https://eth.wiki/en/concepts/proof-of-stake-faqs (accessed Sep. 14, 2021).

[72] G. Pucci. "5 Museums Ahead in the NFT Game." Vastari. (Aug. 13, 2021). [Online] https://blog.vastari.com/5-museums-ahead-in-the-nft-game/ (accessed Oct. 28, 2021).