

NFTs for Art and Collectables: Primer and Outlook

Sarah Allen¹, Ari Juels², Mukti Khaire³, Tyler Kell⁴, and Siddhant Shrivastava⁵

¹Cornell Tech, Initiative for CryptoCurrencies and Contracts (IC3),
E-mail: sarahallen@cornell.edu

²Cornell Tech, IC3, E-mail: juels@cornell.edu

³Cornell Tech, Cornell University, E-mail: mvk34@cornell.edu

⁴Cornell Tech, IC3, E-mail: sk3259@cornell.edu

⁵Singapore University of Technology and Design (SUTD), E-mail:
shrivastava_siddhant@sutd.edu.sg

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Abstract

Non-fungible tokens (NFTs) are digital objects that reside on blockchains and are typically associated with unique digital media, such as images or music. A recent frenzy of popular interest has given rise seemingly overnight to a multi-billion NFT market. Individual NFTs can sell for millions or tens of millions of dollars, while creators ranging from traditional artists such as Damien Hirst and Grimes to mainstream consumer-goods companies such as Coca-Cola and Nike are producing their own NFT collections.

This primer's focus is on NFTs for art and collectables. Our aim is to give non-technical readers a basic familiarity with the technology behind NFTs, the history of their development, the current state of the NFT community and marketplace, and a notion of how NFTs might evolve in the future. We also offer a brief overview of the dynamics of traditional art markets and discuss the similarities, differences, and points of intersection in NFT markets.

We hope that readers will come away from this primer with a basic understanding of how blockchains, smart contracts, and cryptographic keys work, an appreciation of some of the novel ways in which NFTs are empowering artists, a picture of the variety of dynamism of NFTs projects and communities, and possibly a hankering to own at least a fractional Bored Ape.

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1 Introduction

Non-Fungible Tokens (NFTs) are digital representations of unique objects, physical or virtual. Today their most popular use is representation of digital artworks or collectables.

For example, in March 2021 an NFT representing a digital artwork entitled *Everydays: The First 5000 Days*, by an artist known as Beeple, sold at a Christie’s auction for just over \$69 million—the sixth highest price ever paid for a work by a living artist [128]. This event heralded both the rapid ascent of the NFT market and the incursion of NFTs into the traditional art world.

For many people, the ascription of monetary value to NFTs—let alone the sale of an NFT for \$69 million—is mystifying. Ownership of an NFT consists of nothing more than control of a short string of characters on a *blockchain*, as we explain below. This string usually contains a pointer—i.e., an internet address—for a digital file of the work on a server. Anyone can copy the file and view the artwork it contains. (You can view *Everydays* [here](#).) Owning an NFT does not mean a technical restriction on others’ ability to see or download it. Put another way, the owner of an NFT does not enjoy an exclusive access to the artwork she “owns.” An NFT isn’t like a physical work of art, e.g., a painting, which may be displayed in a private space. Additionally, most NFTs don’t confer copyright or other traditional forms of intellectual property ownership.

Despite their oblique representation of ownership—or perhaps because of the resulting flexibility—NFTs have become the cornerstone of a vibrant new art market. This market differs starkly from traditional art markets in the makeup of its community of participants. It also differs in its commission and royalty structures, market dynamics, means of recording provenance, community interactions, and forces shaping the tastes of buyers.

The NFT market is enjoying explosive growth: There was a mere \$13.7 million in NFT sales in the first half of 2020, but over \$2.5 billion in the first half of 2021. NFT mania has swept up not just digital artists and cryptocurrency enthusiasts, but also traditional auction houses (e.g., Christie’s, Sotheby’s [121]), artists known for work in physical media (e.g., Grimes [123], Damien Hirst [132]), and large, consumer-facing companies (e.g., Visa [103], Nike [115]), to name just a few participants.

What does “NFT” mean? The main defining feature of NFTs is their creation and management on *blockchains*. An NFT consists essentially of a short string that is formatted and managed on a blockchain according to one of a few widely embraced technical standards (e.g., ERC-721 [25], ERC-1155 [24]). This string may represent a

small digital work or is commonly a pointer to a file containing a work and resident on a system external to the blockchain (e.g., the Interplanetary File System (IPFS) [30] is a popular choice).

Blockchains first arose as platforms for representing digital units of currency, known as *cryptocurrency*, of which Bitcoin is the best known example. Units of conventional currency are generally *fungible*, meaning that any two units have identical market or exchange value. A U.S. dollar bill, for instance, is interchangeable in commerce with any other U.S. dollar bill. The same is true of units of Bitcoin or any other cryptocurrency.¹

Tokens are a particular form of user-created blockchain object that may take the form of fungible, cryptocurrency-like units. Tokens may also, however, assume a *non-fungible* form. It is such tokens that are known as NFTs.

Like cryptocurrency, NFTs can be bought and sold. NFTs differ from cryptocurrency or cryptocurrency-like tokens, however, in that typically *no two units are interchangeable*. It is in this sense that they are “non-fungible.” For example, the first popular NFTs represented digital cats called CryptoKitties [19, 20]. Each CryptoKitty has unique digital “DNA” with associated phenotypic “Cattributes.” That is, no two CryptoKitties are identical.

Additionally, while cryptocurrency or fungible tokens may be subdivided into small units (e.g., 0.1 BTC), NFTs are not subdividable in the sense that a fractional unit has the same function as a whole unit. An NFT may, however, have multiple, fractional owners, just as a work of art (or other asset) can.

What are NFTs good for? NFTs can represent ownership of any asset that takes the form of unique units. As such, they have many different applications. Art and collectables are one, but NFTs can also in various ways represent real-world objects such as real estate or luxury goods, tickets for events (real or virtual), and characters, items, or “real estate” in online worlds. With the right supporting legal agreements, ownership of an NFT can represent ownership of an asset in a conventional sense. For example, NFT proponents have advocated for the use of NFTs to represent property deeds, and thus full, real-world ownership of real estate [120]. NFTs can also represent serve as identity documents or credentials that are useable on blockchains.

Many blockchains can execute small computer programs, known as *smart contracts*, that are capable of endowing NFTs with powerful features, such as sophis-

¹Strictly speaking, most cryptocurrency is not perfectly fungible. The full transaction history of any given unit of Bitcoin is indelibly recorded on the blockchain. This history sometimes serves in the blacklisting of specific units of Bitcoin obtained from illegal activities, such as ransomware, but the vast majority of Bitcoin is functionally fungible.

ticated market mechanisms. Art-related NFTs, for instance, can enforce payment of a royalty to their creators *upon every resale of the NFT*. This payment regime is unenforceable in traditional art markets, but has been a boon for many NFT artists. It serves as just one example of the ways in which NFTs can radically transform art markets.

Paper goals and organization. This paper consists of three parts. First, we present a primer on the basic mechanics of NFTs for semi-technical or non-technical readers, followed by a brief explanation of the key technologies needed to realize NFTs, specifically blockchains, digital signatures, and smart contracts (Section 2). We review existing scholarship on traditional art-market dynamics and how it conceptualizes artworks and the actors involved in their production and consumption (Section 3). We present a brief history of NFT development, with a focus on NFTs for art and collectables (Section 4), and then provide a snapshot of the current state of the NFT ecosystem (Section 5). Finally, we observe that the technical innovations realized today with NFTs—e.g., new royalty structures—are just the tip of the iceberg in terms of the functional, market, and aesthetic sophistication that blockchains and other technologies can impart to NFTs. We discuss several other, currently unrealized technical and functional possibilities in the realms of art and collectables—and beyond—that NFTs can and may realize in the future (Section 6).

2 A Non-Technical Technical Primer

Much of the impact of NFTs on art and collectables markets can be understood without detailed knowledge of the underlying technologies, such as blockchains. We first present an overview of some basic concepts and how NFT ecosystems operate. For interested readers, we then briefly discuss two advanced tools useful for NFTs platforms today and in the future: *smart contracts* and *decentralized identity*.

2.1 Basic NFT Mechanics

An NFT for an artwork consists of a *digital pointer that is publicly and permanently recorded on a digital ledger*—specifically on a blockchain. This pointer is an address for the content of the NFT, which usually but not always resides *off chain*, meaning in a system separate from the blockchain, e.g., a cloud server or a so-called decentralized storage system such as IPFS [30, 100].² (An NFT may also include a pointer to metadata, e.g., the token name and description.)

Recorded in association with an NFT is an account identifier corresponding to its owner. These account identifiers are (randomized) numerical values, not real-world names, so NFT ownership is pseudonymous by default. Ownership can change, of course: NFTs can be bought and sold or simply transferred to new owners, and thus moved to new accounts.

To understand how NFTs work, it’s important to be familiar with a few key concepts that we now briefly describe: wallets, private keys, minting, and marketplaces. In the next couple of subsections, we provide a little more technical detail on the systems that enable NFTs.

Blockchains. A *blockchain* is an ever-growing list—specifically, an ordered sequence—of messages maintained by a network of servers. There are many different blockchains in use today. The most popular are Bitcoin and Ethereum: As one measure of their popularity, their combined market value exceeds \$1Trn at the time of writing.

The mechanics underlying blockchains can be quite complicated, and are out of scope for this paper. To understand what they do, however, doesn’t require much understanding of how they work. Instead, it is helpful to conceptualize a blockchain as a kind of *digital bulletin board* that contains a sequence of messages with a few special properties:

1. *Append-only posting:* Messages, once posted, cannot be removed.

²Some NFTs with small file sizes are stored on the blockchain, e.g., [11, 41, 15, 26].

2. *Immutability*: Messages, once posted, cannot be modified, nor can their ordering.
3. *World readability*: Anyone can view the full contents of the blockchain, i.e., all messages.

These simple properties enable surprisingly powerful functionality. For example, transfers of NFT ownership on a given blockchain are publicly visible (thanks to their world-readability). They remain so for as long as the blockchain exists and are irrevocable (thanks to immutability and append-only posting).

For more details on how blockchains work, see Appendix A.

Wallets: Because an NFT resides on a blockchain, users must employ blockchain-specific software known as a *wallet* to buy, sell, create, and maintain possession of NFTs. Wallet software runs on a user device such as a mobile phone or a laptop and provides a graphical interface through which users can perform NFT-related transactions.

As the term wallet suggests, wallets also allow users to obtain and transact in cryptocurrency. Use of cryptocurrency is a requirement for NFT buyers and sellers, as NFTs are usually bought and sold using the cryptocurrency native to the blockchains on which they reside.

Cryptographic keys: A wallet’s main function is to hold and secure a (cryptographic) *private key* associated with an NFT owner’s account. There is a corresponding *public key* that serves to identify a user and authenticate her transactions. See Appendix A for more details on keys.

A private key—very loosely analogous to a password—enables the owner to authorize creation, sales, or transfers of her NFTs and receive the proceeds of NFT sales. Conversely, it allows a user to spend cryptocurrency to purchase NFTs and take ownership of them. Possession of the private key for a user’s account thus equates with ownership of the assets in the account. In other words, if a user loses her key or has it stolen, she similarly loses her blockchain assets—cryptocurrency and/or NFTs.

Minting: The creation of an NFT is a process known as *minting*. To mint an NFT, a user—or platform acting on behalf of the user—calls a special function in the smart contract where the NFT will reside. (Some marketplaces have a form of “lazy” minting in which an NFT is minted on the blockchain only when it is first sold or transferred.)

Marketplaces: NFTs for sale can be listed on *marketplaces*, websites that act as front ends for the blockchains on which the NFTs reside. Marketplaces can be viewed in an ordinary browser (even without use of a wallet). In addition to advertising NFTs and intermediating the sale of NFTs, marketplaces also provide technical tools for the creation of NFT smart contracts. In return, they collect commissions on the NFT sales they intermediate.

As an example, one of the largest NFT markets today is OpenSea [36]. OpenSea NFTs reside on the Ethereum blockchain, and NFT prices on OpenSea are therefore quoted in *Ether* (ETH), the native cryptocurrency of Ethereum. (At the time of writing, 1 ETH is worth about \$3000, but prices are extremely volatile.) To create, buy, or sell NFTs, most users interact with OpenSea using a wallet known as Metamask, which is available as a browser plug-in.

Fig. 1 presents a basic schematic of an NFT ecosystem.

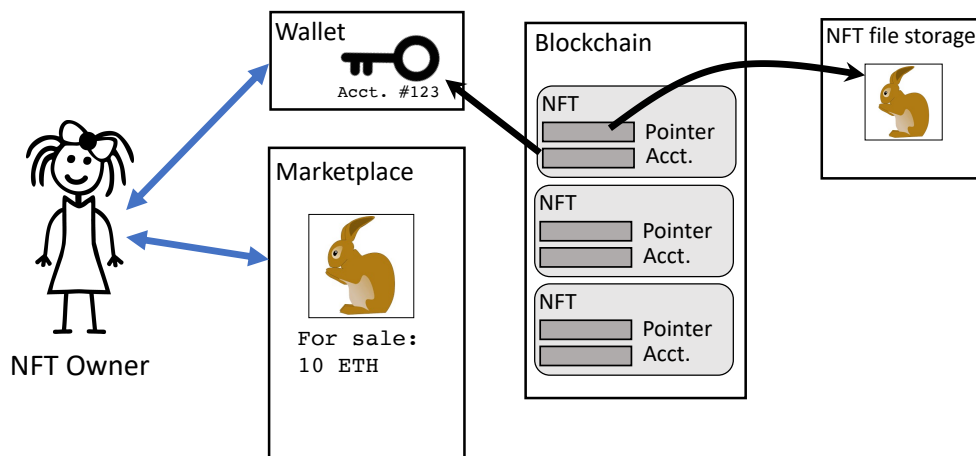


Figure 1: Schematic of NFT system. An NFT consists of a pointer stored on a blockchain along with the owner’s account identifier. The pointer is an address for the file containing the NFT data (e.g., an image or video file). This file resides in storage usually separate from the blockchain, e.g., a cloud server. The NFT owner’s account has an associated private key, which the owner stores in her wallet. This key authorizes sales (or transfers) of her NFTs and also controls her cryptocurrency. A marketplace, in the form of a website, acts as a portal for users, displaying and listing NFTs for sale or auction, as well as intermediating sales and facilitating NFT minting.

2.2 Advanced NFT Tools

NFTs in their most basic form are digital objects that point to off-chain content (or, alternatively, may contain the content). To enable trustworthy buying and selling of NFTs and advanced features like automatically enforced royalties, NFTs must be controlled by smart contracts, as mentioned briefly above. In this subsection, we provide some more detail about smart contracts. We also discuss the concept of decentralized identity, a means of creating privacy-preserving credentials, that is, digital representations of human identities and characteristics.

Smart contracts: It is possible to post on a blockchain not just transactions, but small software applications called *smart contracts*.

Smart contracts can execute transactions that do more than simply move money. They inherit the basic properties of blockchains (immutability and world-readability). In consequence, they offer *transparency*, meaning that anyone can read their code and *integrity*, meaning that they execute exactly as programmed and cannot be modified after the fact even by their creators. In general, therefore, a smart contract can simulate a *trusted third party*, an intermediary that honestly executes financial transactions and can serve as a trustworthy intermediary between people without a pre-established relationship or reason to trust one another.

As a simple example, suppose that Bob wants to sell an NFT to Carol for \$7. Without a smart contract, they have a quandary. Who will transfer her / his asset to the other first?

In Fig. 9, transactions m_2 and m_3 together perform such an exchange of digital assets. In this example, Carol is the first mover: She sends \$7 to Bob before receiving the NFT. Bob could have cheated Carol by not sending her the NFT, i.e., not executing transaction m_3 . Of course, had Bob sent the NFT before receiving Carol's money, Carol could have cheated Bob by not paying. This problem of exchanging goods such that neither party is in a position to cheat is known as the problem of *fair exchange*.

A simple solution is to invoke a trusted third party. For instance, if Bob and Carol both trust Tracy, they could send their assets (NFT and \$7, respectively) to her, and have her perform the exchange. Tracy, however, might charge a large fee for this service, or her NFT-exchange service might go down, or Bob and Carol might be in different jurisdictions, so that one of them lacks strong legal protections in relying on Tracy. Blockchains are designed to facilitate commerce by *eliminating trusted third parties*.

Instead of relying on Tracy, Bob and Carol could instead make use of a smart

contract to *simulate* Tracy’s honest execution of their exchange. A smart contract programmed to perform a fair exchange could, for instance, take custody of an NFT from Bob with a posted sale price (\$7). The contract, then, would accept the \$7 from a buyer such as Carol and upon receiving the money, send the NFT to her.

The transparency of the smart contract would ensure that both Bob and Carol understand exactly what action the contract has been programmed to perform (in this case, a fair exchange). The integrity of the smart contract ensures that it performs this action and cannot be subverted by Bob, Carol, the smart-contractor programmer, or anyone else.

Smart contracts can be programmed to perform more sophisticated actions as well, of course. Today, on a number of different blockchains, they run NFT marketplaces, games of chance, financial instruments, and many other services—all with the trustworthiness of a (virtual) trusted third party.

Furthermore, using systems called *oracles* [137], smart contracts can access reliable, up-to-date information from internet servers. As a simple example, if Bob wants to sell his NFT for \$7 denominated in Ether (ETH), an oracle can fetch the current USD price of ETH to determine how much ETH Carol should pay.

Decentralized identity: Another advanced tool that blockchains—and particularly smart contracts—can make available is *decentralized identity* (DID). Decentralized identity refers broadly to the idea of users controlling their own blockchain-based *credentials*, that is, attestations to personal characteristics. Credentials might attest to a user having obtained an academic degree, living in a particular country, being of legal majority age (e.g., over 18) and thus permitted to sign legal contracts, having purchased artworks online worth a certain amount of money, etc. Credentials can be generated without explicit linkage to users’ real-world identities, and thus can be used in privacy-enhanced interactions in blockchain systems.

One approach to the creation of DID credentials is to have authoritative issuers generate them on behalf of users. For example, e.g., a Department of Motor Vehicles might issue majority-age credentials. Alternatively, recent advances in oracle technology enable use of data on existing websites *without any modifications* to generate DID credentials. (See e.g., [138, 139].)

It is also possible to build DID systems that create unique, per-user credentials (or come close to doing so). For example, a DID system that permits issuance of only one credential per national identifier (e.g., Social Security Number in the U.S.) can achieve this goal. (See [124].)

As we explain in Section 6, DID credentials can be used in a variety of ways to enrich and secure NFT systems.

3 The Structure and Functioning of Art Markets

Art prices are determined by the meeting of real or induced scarcity with pure, irrational desire, and nothing is more manipulable than desire.

Robert Hughes, art critic

Art is the quintessential symbolic good; without the interpretive value loaded on to art, it is merely paint on a canvas. Nevertheless, the symbolic value of art translates into sometimes astronomical figures in real money, and a number of market players are involved in the process of translation for which paint on canvas or a stuffed shark in formaldehyde becomes “valuable” art.

The production, valuation, and consumption of contemporary art are guided by cultural and economic forces that play out in primary and secondary markets. Artists seek the attention of art dealers, who, along with auction houses, play a large role in determining what is and is not innovative and important—and therefore valuable—in the market. Museums, collectors, and critics also play a significant role in affecting public perception and valuation of works of art, while ancillary service providers such as advisors, insurers, and private wealth management and financial services firms support the workings of the market.

3.1 The Structure of the Contemporary Art Market

Artists, firms, critics, outside institutions and buyers constitute the primary and secondary markets for contemporary art. In the primary market, artists sell their works to dealers/gallerists, who sell art to buyers, who could be individual collectors, museums, other dealers, or auction houses. These works may change owners again on the secondary market. The art market, while complex, has evolved over time to this particular structure that constructs and reinforces the aesthetic, cultural, and economic value of art in the market as well as in society more generally. Socio-economic, artistic, and, especially, technological changes and developments repeatedly pose challenges to this structure, while also generating new opportunities [104].

Artists: Artists and their creations are the starting point of the primary art market. A combination of skills, original ideas, and marketing and networking skills lead to artistic success. Artists seek representation by dealers, who can provide them

entry into the art world, build their reputations, give their work exposure and eventually place their works in the collections of important collectors. Artists may either sell directly, or consign works to gallerists or dealers [118].

Gallerists/Dealers: Gallerists (a title they prefer to “dealer”) are typically consumers’ first point of contact with art and artists. Gallerists perform many functions, including, but not limited to: selling art works (in both, their galleries and art fairs) marketing the artists they represent by hosting exhibitions that are typically accompanied by social events like parties, interpreting and explaining art works to consumers, promoting artists and their art in art world publications, and sometimes loaning art to other institutions in service of building artists’ reputations. Galleries are risky enterprises; those that succeed in building relationships with dedicated collectors gain an advantage, but even successful galleries have been known to succumb to competitive pressures. Galleries might have a stable of artists (18-24) and organize single-artist shows about once in approximately 18 months for each artist (depending on the pace at which the artist can work), and/or they buy work from artists, ‘a la carte.

Once gallerists identify artists they wish to represent, they negotiate terms of their relationship, typically foregoing formal contracts due to unenforceability. Thus, dealers and artists are bound largely by moral obligations—the dealer agrees to promote the artist in exchange for rights to exclusive representation and a share of sales. Under such revenue sharing agreements, artists get paid only when the work is sold and therefore have little influence on their earnings—a 50% cut for the gallerist is quite standard. Dealers often serve as “financier, agent, advisor, and friend” for their artists. Often, dealers operate on the secondary market to supplement their primary market activities [133].

Auction houses: Sotheby’s and Christie’s, both established in the 18th century, are also the two largest auction houses in the 21st century, with powerful brand recognition. The two houses hold auctions of contemporary art on consecutive evenings – a high point in the art world, an event that attracts worldwide buyers.

Auction houses must promote an aura of prestige and exclusivity in order to succeed; purchases at auctions are expensive, but collectors remain loyal because a work from a reputed house grants a certain cachet and status. Auction houses, which traditionally operated only in the secondary market, entered the primary market in the first decade of the 21st century, posing a challenge to the market position of galleries/dealers [118].

Buyers (Collectors and Art Investors): Art collectors range from dabblers through art aficionados to serious investors, with the most serious high-spenders being a small and exclusive group. Wealthy collectors are often advised by professional art consultants and can influence the perceived aesthetic and economic value of works because provenance (chain of ownership) plays an important role¹³ in the valuation of works of contemporary art; being a part of the collections of individuals known for their discernment can add value to an artist’s name and work. Today, since the start of the 21st century, art collection is a global phenomenon; collectors hail from an increasing number of nations, including developing regions, across the globe [133].

As the contemporary art market has exploded, however, individuals buying art for art’s sake have been joined by individuals with an investor mentality, buying art works with the intention of reselling them for a higher price. However, gallerists purportedly disapprove of such “flippers,” and the negative effect they have on the smooth functioning of the art market, and are unlikely to sell works of well-known artists to individuals believed to be interested only in buying works as investments, or to flip them. Therefore, gallery-owners generally sell important works largely to individuals they know well and know to be “serious” collectors, a practice that has led to the belief that the primary market is a small, clubby, closed world, not open to novice collectors.

Art investment funds, which first appeared in the mid-late 20th century, have not been unequivocally successful, presumably because the diffuse artistic economy and the non-pecuniary motivations of artists as well as the largely symbolic value of art make it difficult to achieve consistent returns in art investing [133].

Museums: Museums are known, and expected, to operate outside the art market, to inform and educate consumers of art through exhibitions of their high-quality collections curated by their expert staff. Museums influence the art that will be seen by critics and the public, and thus, can help build the careers of artists. That said, the impact of museums on transactions and prices in the art world is indirect and difficult to pinpoint precisely because they are “outside” the market. However, their purchases are often permanent, due to which having even a single work included in a museum’s collection often benefits the artist by raising his/her public profile, and adding respectable provenance to their pieces [104].

Critics: Critics evaluate and explain art works based on their training, which gives them an understanding of aesthetic systems and the attributes that render art worthy and valuable. Critics’ commentary on art works shapes public discourse on art, which can generate and reinforce conceptions of ‘good’ art among the public and influence

how specific artists and their works are valued. Indeed, “critics are sometimes more important than creators,” said sociologist Herbert Gans, “because they determine whether a given cultural item deserves to be considered high culture, and because they concern themselves with the aesthetic issues which are so important to the culture” [116].

The commentary of critics takes the form of reviews, feature-writing, or summary. These writings serve both evaluative and reputation-building and validating functions for artists

4 A Brief History of (Ethereum) NFTs

The NFT trend may have accelerated dramatically in 2021, but it has roots as early as 1993, in the “cypherpunk” community. That community includes proponents of the use of cryptography and privacy-enhancing technologies as means to achieve social and political change.

In this section, we offer a brief history of NFTs, one meant to enable the understanding of how NFTs evolved, but not to be exhaustive or editorial in nature. We group the history of NFTs into four epochs. Section 4.1 covers the earliest forms of NFTs, before the advent of Ethereum. Section 4.2 discusses early experiments with Ethereum-based NFTs before standardization and popularization of the technology. Section 4.3 talks about the catalysts that enabled NFTs to rise in popularity, and Section 4.4 discusses the NFTs that took the main stage of popular crypto-culture. We complete this timeline in the next section, Section 5, where we discuss the final epoch and survey the NFT ecosystem as it exists today.

4.1 The Earliest NFTs

The history of NFTs, like their technological underpinnings, is intertwined with the history of cryptocurrencies. Proto-cryptocurrencies emerged as early as the late 1980s and early 1990s, e.g., DigiCash [105], a centralized but privacy-preserving form of digital cash. Some in this early community envisioned the emergence of digital assets with properties like those of non-fungible tokens.

One notable example is a prescient, satirical email-list post (Fig. 2) in 1993 by Hal Finney, a very early Bitcoin user (hypothesized by some to have been Satoshi Nakamoto, the creator of Bitcoin [119]). Finney’s post proposed a conceptualization of digital cash as ‘Crypto Trading Cards,’ emphasizing the unique properties of each card / coin and appeal to hobbyists (as opposed to the fungibility, i.e., interchangeability of currency) [113]. As early as two decades ago, digital-currency pioneers were considering the possibility of unique, cryptographically authenticated data with the properties of rarity and scarcity.

While NFTs found cultural popularity on the Ethereum blockchain, the earliest instance of an image embedded in a blockchain is believed to have appeared in Bitcoin block 138725 [12, 50] in 2011.³ Soon afterward, in 2012, *colored coins* emerged on Bitcoin [17, 129]. They represented the first instance of a blockchain being used to realize a token distinct from its native cryptocurrency. A colored coin is a denom-

³It was a piece of ASCII art, an image composed of letters and punctuation marks. The image was a portrait in memory of a recently deceased man named Len “Rabbi” Sassama.

Crypto trading cards.

- *To:* CYPHERPUNKS <CYPHERPUNKS@TOAD.COM>
 - *Subject:* Crypto trading cards.
 - *From:* Hal <74076.1041@CompuServe.COM>
 - *Date:* 17 Jan 93 13:48:02 EST
-

Giving a little more thought to the idea of buying and selling digital cash, I thought of a way to present it. We're buying and selling "cryptographic trading cards". Fans of cryptography will love these fascinating examples of the cryptographic arts. Notice the fine way the bit patterns fit together - a mix of one-way functions and digital signatures, along with random blinding. What a perfect conversation piece to be treasured and shown to your friends and family.

Plus, your friends will undoubtedly love these cryptographic trading cards just as much. They'll be eager to trade for them. Collect a whole set! They come in all kinds of varieties, from the common 1's, to the rarer 50's, all the way up to the seldom-seen 1000's. Hours of fun can be had for all.

Your friendly cryptographic trading card dealer wants to join the fun, too. He'll be as interested in buying your trading cards back as in selling them.

Try this fascinating and timely new hobby today!

Hal

Figure 2: Hal Finney's email from 1993, which mentions the idea of "cryptographic trading cards."

ination of Bitcoin that carries metadata designating its use for a purpose unrelated to cryptocurrency. Colored coins were proposed as a means to represent coupons, real-world property, company shares, etc. There was no notion at the time of linking them to works of digital art.

NFTs, in the current artistic sense of the term, first appeared in 2014. While there are a few contenders vying for the distinction [33], Sotheby's recognizes Quantum [42] as the first art NFT ever minted. This five-second animated work of digital art, was minted on 2nd May 2014.⁴ These NFTs and others may be found in an NFT-focused online museum called the Museum of Crypto Art [5]. It archives NFT artwork projects dating since the early 2010s.

NFTs were originally minted on Bitcoin via a service called Counterparty [106]. Ethereum has been the dominant platform today for NFTs. Consequently, we focus for the remainder of this section on NFTs in Ethereum.

⁴More precisely, in Namecoin Block 174923. It was preserved in a reminting on 28 May 2021, as Namecoin's unusual design caused the original NFT to disappear.

4.2 Early Ethereum NFTs

The first Ethereum NFT was Etheria [99].⁵ Etheria implemented a form of virtual real estate as a board consisting of hexagonal tiles. Individual tiles were represented by NFTs that could (and still can) be bought and sold via an Ethereum smart contract. Etheria was presented at the second Ethereum developers’ conference, Devcon 1 [111]. More than 450 of Etheria’s 914 tiles went unsold for over five years, until March 13, 2021, when the project creator reminded the community via Tweet of the long dormant project. Etheria also contains what is believed to be the first NFT house [112].

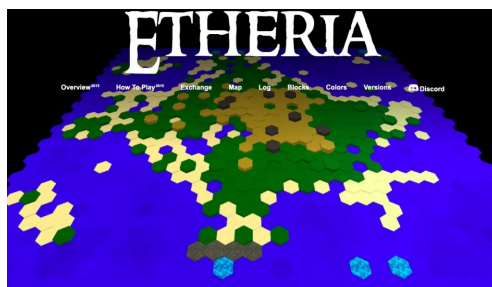


Figure 3: Etheria: digital land as NFTs

The first NFT art gallery ever created, in October 2015, was left gallery [4]. It is still operational at the time of writing.

Even in their early history, NFTs were not limited to photographs or drawings: There were audio NFTs as well. The first NFT to incorporate sound is attributed to the DJPepe project in 2016 [9] on the Bitcoin blockchain.

4.3 2017-2018: NFT Foundations Are Laid

The year of 2017 witnessed as the “ICO boom,” an explosion of new applications for Ethereum fungible tokens. That year also saw the launch of a number of historically important NFT projects, some of which remain key parts of the NFT ecosystem depicted in Fig. 4. These projects are also influential in steering the dominant discourse around NFTs today. Many projects launched in 2017 are notable for being the first project of a particular *category*. Decentraland, for example, was the first ETH-based “metaverse” project: It is realized in virtual reality, and facilitated with

⁵There is some debate as to whether objects in an older project, Terra Nullius, constitute true NFTs [136].

NFTs. Cryptokitties was the first successful NFT-based blockchain-based game, and inspired many of the blockchain games we see today. Cryptopunks invented the idea of a profile-picture collection of NFTs.

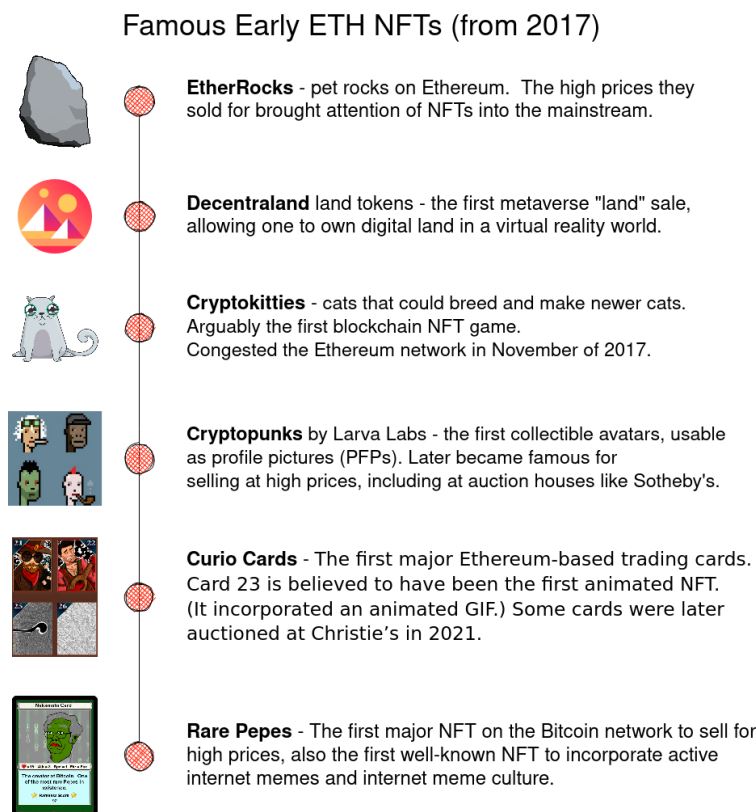


Figure 4: Some notable NFT projects released in 2017, with a description of why they are important.

The period from late 2017 into early 2018 also saw the advent of two important and enduring catalysts for trading of NFTs on secondary markets [126]: *marketplaces*, such as OpenSea, and *standardization*, specifically the introduction of the ERC-721 token standard, a standard making NFTs interoperable across smart contracts.

Launched in December 2017, OpenSea was the first peer-to-peer marketplace for NFTs. As of March 2022, it has become the biggest marketplace for such items, with over 1.5 million users regularly performing more than \$2+ billion a month in trade volume every month.[81] Other prominent exchanges, launched in 2018, include SuperRare.io and KnownOrigin.io.

The ERC-721 standard for NFTs [25] was released by OpenZeppelin shortly after the creation of OpenSea, in March 2018. ERC-721 is an open standard that defines how NFTs must be specified and implemented. Prior to ERC-721, projects had to implement custom smart contract code for their NFTs, resulting in an inability for NFT smart contracts to interface with one another and consequently in marketplace friction and poor user experience. ERC-721 includes standardized interfaces for smart contracts that manage NFTs, and thus enables NFTs to be transferred between smart contracts created by different entities. This interoperability helped catalyze the NFT ecosystem.

4.4 2018-2020: The NFT Community Expands

The period from 2018 through 2020 was a period of growth in which creators experimented with NFT to little fanfare. The community was still relatively small and not in the public spotlight. In January 2018, the first NFT conference event was organized: the Rare Digital Art Festival (R.A.R.E.). The genesis of the event was a tweet, shown in Fig. 5. Twitter has continued to play a major part in catalyzing the rise of NFTs and in community evolution (as discussed in Section 5). R.A.R.E. has since been overtaken in popularity and size by other events, such as NFT.NYC [79] and NFT.LA [78].



Figure 5: The tweet that led to R.A.R.E., the first significant NFT event.

NFT promotion also leveraged radio-themed formats: The first NFT-themed podcast, called Digitally Rare, launched in July 2018 [58]. The first magazine devoted to NFTs, MagNFT, was released in late 2019 [75]. The first newsletter dedicated to NFTs, Nifty Report [45], was released in December of 2019. All three still produce content today.

The NFT community first started to interface with the traditional art world during this period as well. As discussed in Section 3, the first instance of a piece of fine art from the physical/traditional art world being tokenized, i.e., represented in the form of NFTs, took place in September 2018. A 31.5% stake of a (physical) Andy Warhol painting entitled *14 Small Electric Chairs*—shown in Fig. 6—was sold through a smart contract on the Maecenas auction platform to multiple investors for \$1.7 million. 800 bidders participated in the auction.

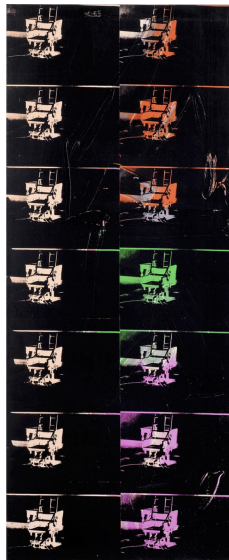


Figure 6: Andy Warhol’s *14 Small Electric Chairs* (1980)

Such sales of physical artworks via NFT have become popular in part because they offer a simple vehicle for *fractional* sales of works and offer investors a sense of ownership more direct than investment in an art fund. For example, a former Christie’s executive has created a company called Particle whose mission is to divide works of art into 10,000 shares (called “particles”) for sale to investors [107].

The conversion of tangible goods into intangible assets has led to various forms of philosophical commentary on the interplay between physical and NFT art. For example, a group associated with the Twitter handle @burntbanksy livestreamed the burning of an original Banksy print (a 1/500 piece entitled ‘Morons’). They subsequently sold an NFT representing the destroyed print. [16]

During this period artists also experimented with new types computer generated art, with aspects unique to the NFT technology. In April 2019, Autoglyphs by Larva

Labs [49] became the first on-chain *generative* NFT artwork. A generative artwork is one produced by computer code in a manner that is at least partially autonomous, i.e., without full guidance from the artist. In the case of generative art in NFT, the code itself forms part of the NFT, and takes computer inputs from the NFT. This phenomenon is not limited to paintings: In February of 2021, Eulerbeats [26] pioneered the first instance of on-chain algorithmically generated music NFT, that is, the music that was produced was produced in the art piece is the output of a computer program with inputs and outputs stored on the blockchain in NFT form.

4.5 2020-2021: The NFT Community Hits Critical Mass

The year of 2020 marked the beginning of mainstream artists publishing their work in the form of NFTs. The sale of 10 NFTs for \$6 million in December of 2020 by the Canadian musician Grimes was a landmark event in the music community [135]. By early 2021, *Rolling Stone* declared that music NFTs had gone mainstream, noting that *Kings of Leon* became the first band to release a new album as a non-fungible token (NFT) in March 2021—with great success [117].

In summer 2021, prominent traditional artist Damien Hirst [7] announced the sale of a series of 10,000 hand-painted dot-covered works on paper entitled *The Currency*. He gave buyers the option of receiving the physical work or having it destroyed and represented as an NFT.

Well known auction houses such as Sotheby’s [66], Christie’s [53], Phillips [102], and others also started to conduct NFT sales [131] as NFTs caught the eye of influential artists. One prominent example of the burgeoning acceptance of NFTs in the art community was the \$69 million sale by Christie’s of the NFT art piece “Everydays” [63, 128] by digital artist Mike Winkelmann [47] (artist name Beeple). This sale propelled NFTs into the media spotlight and Beeple to fame outside the cryptocurrency-art circles in which he was previously known.

In the next section, Section 5, we examine the most recent past year of NFT history, and discuss the current shape of the NFT ecosystem.

5 NFTs in Early 2022

Just as technology development for cryptocurrencies is advancing at a breakneck pace, so too are technologies and fads in the world of NFTs. A description of what purports to be the current state of the NFT ecosystem would no longer be current after a few months. Therefore we instead offer a snapshot of the NFT landscape in early 2022, spotlighting what we view as the most significant emerging and popular forms of NFTs, with an emphasis on art and collectables.

We organize this snapshot of the state of the NFT industry into three separate pillars: Section 5.1 deals with who the market participants are, Section 5.2 considers what types of NFTs they interact with, and Section 5.3 discusses the places where these market participants interact.

5.1 Types of Market Participants

Our interviews with NFT artists and enthusiasts suggest that the NFT community often taxonomizes its members into one of four roles: *collectors*, *creators* (artists and developers), *investors*, and *flippers*.

Of course, this taxonomy is a loose one. A given individual or organization may assume more than one of these roles and may transition between or among roles over time. Indeed, a buyer’s motivation for acquiring an NFT may be multifaceted. Nonetheless, we believe these categories offer a fairly accurate notion of how the community itself perceives its members.

Type	Description	Examples
Collectors	People that systematically collect NFTs	DCInvestor [22], Punk6529 [39]
Investors	People that buy for long-term NFT price appreciation	Three Arrows Capital [96]
Flippers	People that buy for short-term trading profits	MEVCollector [77] Sneakyninjapants [95]
Artists and Developers	Creators	Farokh [64], FVCKRender [72]

Collectors: As suggested in Section 3, the term *collector* often refers in the world of traditional art to an individual who acquires art as an aficionado. Some NFT buyers have similar motivations. For instance, both DCInvestor [22] and Punk 6529 [39] have

publicly claimed that they collect early works of on-chain generated digital art for the sake of preserving them for future generations, e.g., in a virtual museum, visitable by the general public on the Internet [37, 38, 87]. Indeed, both celebrities and wealthy individuals without backgrounds in cryptocurrencies or blockchain technologies have become collectors of high value NFTs [101, 46].

Creators (Artists and Developers): Artists and smart contract developers create the art and infrastructure that support the NFT ecosystem. Many of them come to acquire NFTs, not infrequently as gifts from friends or fellow artists. As such, they constitute a special class of collectors and tastemakers. While there have been examples of famous artists who were or are also collectors (e.g., Damien Hirst [7]), the ease with which relationships can be formed and NFTs can be transferred has made interactions among creators especially vibrant within the NFT community. For instance, creators will partner to host digital events. Creators in the traditional art world have held co-hosted events as well, but the speed and geo-diversity of Internet culture means artists can hold digital events more often and more easily than events at a gallery. For example, the prominent cryptoartist Farokh [64] holds weekly podcasts with other NFT artists, which are accessible to anyone with an internet connection, in contrast to the exclusive events held by traditional galleries in the physical world [89, 90]. Another prominent NFT artist, FVCKRender [72] is well known in the community for being an avid collector as well as artist. His OpenSea profile, for example, shows that he owns over 1500 NFTs created by other artists [71].

Investors: Another category of NFT buyer is those who seek to earn a profit over the long term based on astute anticipation of the NFT community’s evolving tastes and market dynamics. Some of these investors, both individuals and institutional investors, resemble those in traditional art markets, as discussed in Section 3. Examples of the latter include Three Arrows Capital [96, 97]. They are known for collecting computer generated digital art pieces from a well-known curated online NFT Art gallery called Art Blocks [48] and describe themselves as “a hedge fund established in 2012 and focused on providing superior risk-adjusted returns.”

Smart contracts, however, have also given rise to NFT investors for whom counterparts in the traditional art world are rare or non-existent. For example, many NFT investors invest in fractional ownership or shares of high-value works of art, a relatively unpopular practice in traditional art markets. For example, fractional.art [69] allows any owner to fractionalize her or his NFT in a smart contract vault, which issues partial shares of the NFT that can then be traded and sold. This practice

allows investors to gain exposure to NFTs they could not afford to own in their entirety.

Some investors invest in NFTs by way of *Decentralized Autonomous Organizations (DAOs)*, smart contracts that realize institutional investment with governance rules enforced by code. For example, members of SharkDAO [91] use a DAO to fractionalize Nouns [80], an expensive variety of NFT. There are many similar DAOs for other high-value NFTs, e.g., CryptoPunks, Bored Apes, etc. (See Section 5.2 for further discussion of DAOs for NFTs.)

Flippers: The last category of participant in the NFT ecosystem are flippers: a special class of investor who hold NFTs for very short periods of time. As discussed in Section 3, flipping is frowned upon and discouraged in traditional art markets. In NFT markets, it is a common practice, however (although it can be and sometimes is prevented by having smart contracts enforce minimum holding periods on NFTs). Many NFT flippers exhibit behaviors like those of arbitrageurs in traditional financial markets: They employ technically sophisticated strategies to exploit arbitrage opportunities between different marketplace platforms, gain priority access to NFTs before the general public to sell at a higher price (frontrunning [108]), and so forth. Indeed, some prominent arbitrageurs such as MEVCollector [76, 77] and SneakyNinjaPants [94, 95] publicly discuss and arbitrage both cryptocurrency and NFT transactions in search of profit.

5.2 NFT Categories

Viewed from a purely technical perspective, an NFT is just label pointing to an arbitrary piece of data, as discussed in Section 2. In practice, we find that the NFTs that are popular and command high prices generally fall into one of a small number of categories. We enumerate these categories in Table 1 and discuss them in the text that follows.

Fine Art NFT Projects: “Fine Art” NFT projects aim to create works to be appreciated for their artistic or stylistic merit. The NFT creators make no promises of future use cases for their NFTs, other than the persistent availability of the associated artworks. Just as the traditional art world has had different stylistic movements and genres, fine art NFTs assume diverse and evolving forms.

A technologically novel type of NFT art that has become popular is *procedurally generated* or *generative*. This category of NFTs was pioneered primarily by the Art

Category	Examples
Fine Art	Art Blocks, Organic Growth Crystal Reef, Brotchain, Fidenza, Damien Hirst’s Currency
Profile Picture Collections	Cryptopunks, Bored Ape Yacht Club
Collectibles	Parallel Cards, NBA Top Shot
Crowdfunding Media Production	Treeverse, ETH-MEN, Shibuya
Grassroots Community Building	Loot, n project
Fractional Ownership	Fractional.art, SharkDAO, Founders DAO
Identity Tokens	Proof of Humanity (PoH), Proof of Attendance Protocol (PoAP)

Table 1: A taxonomy of popular NFTs.

Blocks project, a digital art gallery team that partners with artists to release collections of generative procedural art with accompanying NFTs. A piece of generative art consists of two parts: a generative algorithm (a procedure, computer program) that generates artworks, and a “seed input,” a numerical value fed to the algorithm that determines the artwork that results—be it an image, video, or even music. A seed input generally derives from some characteristic of the NFT, such as its unique token ID, which is analogous to a serial number. (In some cases the token ID is processed using a cryptographic hash function—essentially a form of scrambling.) A single generative algorithm may be used with multiple distinct seeds to produce multiple distinct artworks.

The most prominent examples of this type of generative NFT “fine art” include The Chromie Squiggles [54], Fragments of an Infinite Field [70], and Fidenza [65].

Other types of fine art exploit specific fundamental characteristics of the Blockchain ecosystem on which they live. For example, the Organic Growth Crystal Reef project [82] exploits the fact that the history of trading of an NFT remains permanently on the blockchain. An NFT in this project is an image of a crystal that mutates every time the NFT is traded, i.e., is purchased by or given to a new owner.

As we have noted, the images or other media associated with NFTs are often stored in systems separate from the blockchain in which the NFT itself resides. Some

projects seek instead to store as much NFT data as possible on the NFT’s blockchain, in a quest for on-chain NFT “purity.” Some NFTs of this kind store both their seed information and the code that produces the associated artwork on-chain. Smart contract code is then able to render the artwork. This methodology is embraced by projects that use the Scalable Vector Graphics (SVG) image format, such as solSeedlings [41], and others such as Brotchain [15] whose artworks are fractals.

The majority of fine art NFTs incorporate no special properties of the blockchain on which they reside, but merely point to a piece of digital artwork that resides off-chain, i.e., in a separate system designed for storing files. An example would be the digital versions of the works in Damien Hirst’s The Currency [21] collection.

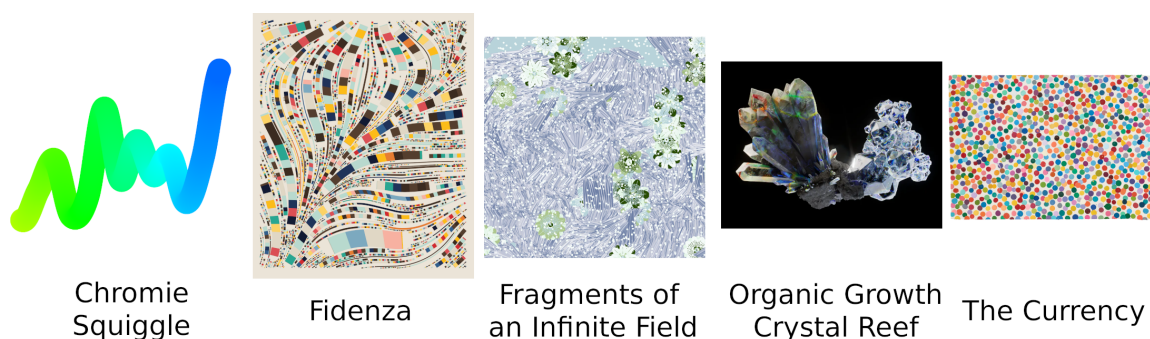


Figure 7: Examples of various fine art NFTs.

Luxury Brands and Profile Picture Collections: Another emerging category of NFTs is those that sell themselves as explicit social status signaling brands, like luxury clothing brands. Cryptopunks [73] and the Bored Ape Yacht Club [51] are the most famous of these examples. Both of these projects are considered “profile picture (PFP) projects.” This means that owners of these NFTs often use their NFTs as online avatars for social networks; the NFTs thus serve as social signaling goods, in much the same way that luxury clothing/jewelry is a Veblen good (goods where demand increases as price increases) signaling status in the real world. In some ways, these digital goods are more effective than luxury clothing, because a profile picture is visible to the entire internet community, unlike clothing, which signals to others only in the owner’s immediate physical vicinity. NFTs are nonetheless also branching out into luxury clothing in the physical world: Bored Ape Yacht Club-branded merchandise, such as their hooded sweatshirts, sell for hundreds to low thousands of dollars on eBay, and projects like RTFKT (pronounced “artifact”) [88]

create themed physical sneaker shoes specifically for holders of projects like the Cryptopunks.

Collectibles: While some would view the 10,000 unit collections of pictures of pixelated punks or bored looking apes as collectible toys themselves, traditional physical collectibles are also migrating to the NFT world. The Parallel Card [83] project produces 3D-animated trading card NFTs of characters and artifacts that are used to construct decks of digital cards to be played in a future online / mobile game.

A more mature project, NBA Top Shot, created by the founders of the very early proto-NFT CryptoKitties project [57] in partnership with the National Basketball Association of the U.S., allows collectors to purchase collectible video-snippets of highlights (as opposed to trading cards of players) of recent NBA games stored in NFT form on the proprietary, centralized (controlled entirely by Dapper Labs) Flow [67] blockchain. The use of video distinguishes such NFTs as an *entirely new category of digital collectible*, unlike traditional collectibles such as cards, bobble-heads, or signed photographs from earlier centuries.

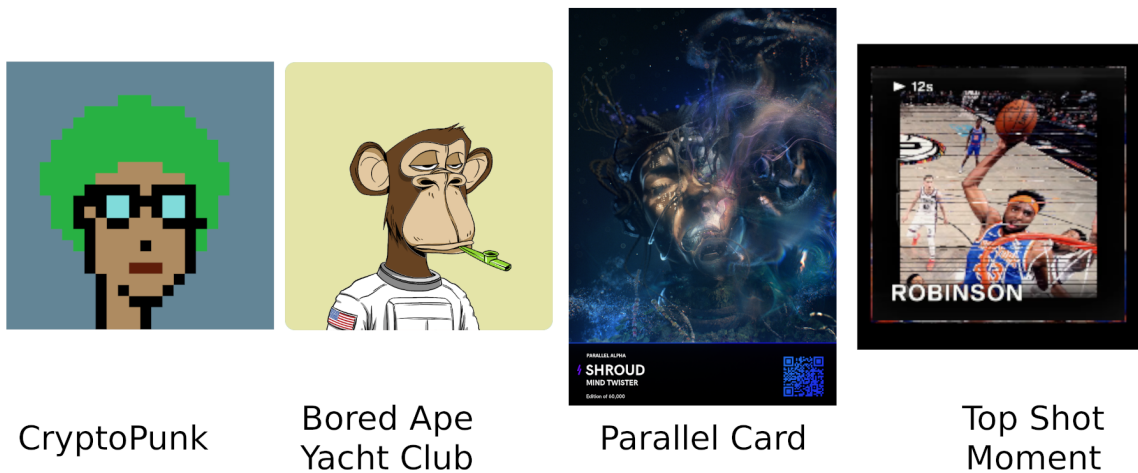


Figure 8: Examples of various Collectible NFTs.

NFTs as a Crowdfunding Mechanism: Many projects in the NFT ecosystem use the sales of collections of art NFTs as a means of selling the intellectual property rights to a character or participant in a soon-to-be-developed media collection (like a comic, movie, television show or game). The proceeds then bankroll further

development of the media project, in a manner akin to crowdfunding sites like Kickstarter or GoFundMe. In the existing ecosystem, these NFT projects tend to focus on building ecosystems of intellectual property, stories and artwork associated with the NFT collection, slowly growing an entire media franchise centered around the NFTs.

Examples of this kind of crowdfunding NFT in gaming include Treeverse [98] and Colony Online [55], both of which sold NFTs to raise money for development of Massively Multiplayer Online Role Playing Game (MMORPG)-style video games. For example, Treeverse sold NFTs that were meant to be used in the upcoming game as private homes for owners of plots of land. In Colony Online’s case, the NFTs represent animal characters meant to be used as the sprite, that is, the avatar, of the owner while interacting in the game-world.

Comic-startup companies have also used NFTs as a means to bootstrap a project: Both PixelVault PUNKS Comics [84] and ETH-MEN [62] sell NFTs for tokenized comic books such that access to read the comic is restricted to people that have purchased the token.

The PUNKS Comics project uses NFTs in a novel way. That project promises that in the future, a physical comic book they create will be mailed only to people who participate in a “burning” event in which users render their tokens unusable by transferring them to a special address that no one controls [84].

NFTs have also bled into video media. For example, the Forgotten Runes Wizards Cult [68] project used proceeds from the sale of a group of 10,000 wizard-picture NFTs to fund a partnership with the animation studio Titmouse to produce an animated television show about the lives of the wizards in the NFT collection itself [6]. The Shibuya.xyz project [92] is producing an Anime television show. The team behind the project sells “episode” NFTs on a regular basis that allow the person who purchases the NFT to vote on the trajectory that the episode will take, similar to the decision points in a choose-your-own-adventure game [93].

Grassroots Community Building: Loot and Successors: The majority of NFT projects discussed thus far have one thing in common: A single artistic authority produced the content. An alternative has arisen in bottom-up grassroots projects that decentralize the artistic authority of NFT content creation. Such projects effectively advocate for unstructured community development around a common set of NFTs.

The seminal Loot project [74] was the first major such project. It was the brain-child of Dominik Hofmann, one of the founders of the video-sharing app Vine. Loot is a collection of NFTs in which the content of each NFT is a randomized list of

text descriptors corresponding to the types of items featured in video adventure games as collectible “loot.” (E.g. “Leather Boots,” “Divine Robe,” or “Platinum Ring.”) The idea behind Loot is that once the parent collection of NFTs was created, the community became responsible for creating additional content that endowed the NFT with meaning. In other words, the community around the project both creates the additional content and identifies what content becomes culturally relevant to the survival of the project. This kind of anarchistic approach works well online, as motivated participants can self-organize on existing social-media networks.

In the case of Loot, this self-organized anarchistic community created many additional assets: a token called Loot Gold (AGLD) to represent the currency used in the loot universe, visual NFTs corresponding to the text descriptions, and subcommunities built around collecting loot-bags with specific characteristics (e.g., collecting Loot NFTs that contain “Divine Robes” [59, 60]). Additionally, many derivative projects were created that centered around text descriptions of other game-culture characteristics, such as non-player characters (NPCs), craft materials, in-game food, maps, and more.

One unique project that took inspiration from Loot’s anarchistic approach is the N-project. In the N-project, the parent NFT is a list of numbers publicly generated in a way that offers a mathematical assurance of randomness (specifically, what is known as “pseudorandomness”). The idea is that any digital artist that uses randomness in their art (effectively all artists producing procedurally generated pieces) can draw that randomness from an N-project NFT and sell a corresponding artwork to the holder or holders of that N-project NFT. Thus the N-project NFT becomes a hub for artworks that all center around the N-project and its community.

Decentralized Autonomous Organizations (DAOs) for NFTs: A Decentralized Autonomous Organization (DAO), as mentioned above, is an organization governed by code stored on an Ethereum smart contract. DAOs for cryptocurrency originated in the early history of Ethereum [127]. Many recent NFT projects use their NFT tokens as membership tokens in a DAO project.

One use of NFTs for DAOs is for governance: An NFT represents some unit of voting power in a political system for voting on proposals issued by the DAOs leadership. For example, one project that uses NFTs for voting is Doodles [61]. The Doodles project maintains a treasury for the purposes of investing and growing the Doodles brand. This includes hiring full time staff to work for the project, financing partnerships and holding events at NFT conferences. The holders of the Doodle NFT then vote on proposals for how to responsibly spend this money.

The other main use of NFTs for DAOs is to represent fractional ownership. With

this approach, which may or may not also include voting mechanisms, the NFT itself represents ownership of a share of some treasury. One example of this category of NFT is the Pixel Vault Founder’s DAO NFT [84]. (Recall that Pixel Vault is the company behind PUNKS Comics mentioned in the prior section on crowdfunding.) In this DAO, an NFT does not let you vote on the actions taken by the Pixel Vault company, but rather represents a partial share in a treasury that holds content related to PUNKS Comics. (That treasury also holds some unaffiliated high-value NFTs, such as several CryptoPunks and Bored Ape Yacht Club NFTs.)

Real-World Interaction Tokens and Identity Tokens: One last NFT collectable trend in the current ecosystem are identity tokens that serve as both as collectibles and as tokens that prove some sort of fact about a human being. One example of this is the Proof of Attendance Protocol (PoAP) ecosystem [85]. PoAP NFT tokens are intended to be given out by organizers at conferences as conference swag, like stickers or tee shirts. Often these tokens will have a corresponding piece of art for that year’s conference attached to the token. Later, anyone can verify ownership of a PoAP token, and view the list of tokens for attendance to each unique event. These tokens can then be used by groups that want to only interact with people that attended certain conferences or real-world events.

PoAP tokens are subvertible, in the sense that cheating conference organizers can distribute fake credentials. For higher quality identity NFTs, the Proof of Humanity (PoH) [86] project grants NFT tokens to Ethereum users who prove they’re a human. The PoH system requires submitting video evidence answering a list of questions, and it also utilizes a system in which people must have other people “vouch” for their humanness and the uniqueness of their asserted identity.

Today, identity NFTs are not widely used. Their use has been limited to gating access to NFT-related parties or to opportunities to purchase new NFTs [52, 134]. We believe, however, that identity NFTs will assume a much larger role in the NFT ecosystem in the future. We discuss this idea in Section 6.

5.3 Places Market Participants Interact

The global NFT community today primarily coordinates activities and discusses NFTs via popular social media platforms. Trading of NFTs is performed via marketplace websites, which, as noted above, provide escrow services and easy-to-use interfaces that list NFTs for purchase or sale.

NFT Communities: Some discussion and interaction among NFT market participants occurs on sites like Instagram, Facebook, and Tik-Tok, but the majority happens on two social media networks: Twitter and the Discord chat application.

Typically an NFT community will create a Discord server (a chat server) for community members, with gated chat channels only accessible to members that have proven ownership of an NFT in the associated collection. The largest of these communities tend to include tens of thousands of users. For example, as of March 2022, the Bored Ape Yacht Club has 148,000 Discord users, and the Larva Labs (the company behind Cryptopunks, Autoglyphs, and Meebits) Discord has 56,000 registered users.

Twitter too serves as a platform for discussions among influencers, thought leaders, and regular users. Commentary on Twitter is more public than Discord, since all Tweets are fed into one central timeline, as opposed to the segmented chat servers of Discord. Unlike the case in many industries, in the NFT space many influencers on Twitter have dedicated pseudonymous accounts that discuss only NFTs and display expensive collections. Examples include Cozomo de Medici (confirmed to be the famous rapper musician Snoop Dogg), who as of March 2022 has 214.3K followers [56] and Punk 6259 who has 285.4K followers [39]. Traditional “influencers” also take part: Artists and celebrities such as Steve Aoki [43], Logan Paul [31], and DeadMau5 [23] partner with different NFT collections, promote them on Twitter, and even release their own NFTs. Twitter has embraced the NFT community, even offering a feature in its paid Twitter Blue subscription service that allows users to distinguish their NFTs as their profile pictures with hexagonal portraits, as opposed to the usual circular portraits of non-NFT users. The service validates that the NFTs are actually stored on-chain, but does not limit which NFT collections are allowed to be used or validate that the NFT collection itself is legitimate or fake in any way.

NFT Marketplaces: Many NFT Marketplaces have emerged to meet the needs of the participants in the NFT ecosystem who wish to buy, sell and trade NFTs. NFT Marketplaces such as OpenSea [36], Rarible [40], and LooksRare [32] offer familiar e-commerce interfaces for buying and selling NFTs, reminiscent of eBay or Amazon, with features such as auctions and “buy-it-now” listings.

These marketplaces vet artist-created NFT collections, attempting to ban fraudulent, scam and, copycat projects. Marketplaces also verify the legitimacy of NFT collections to facilitate safety for users in their purchases. They may highlight such a collection with, e.g., blue checkmarks next to the collection name on the website. Scammers often create copycat collections consisting of stolen artwork with which they attempt to defraud customers. Such scam collections should in general

be unable to obtain “blue checkmark” status.

NFT marketplaces commonly also provide tools for artists to launch their own NFT collections. Artists’ profiles and offerings can be directly integrated into the marketplace website, so that artists need not maintain their own websites.

Some NFT marketplace platforms try to specialize in a specific niche. For example, SuperRare [44] and Foundation [27] specialize in 1/1 unique artworks from established artists, while NiftyGateway [35], FTX [28], Crypto.com [18] and others focus on tightly integrating with cryptocurrency exchanges, providing easy-to-use tools to purchase NFTs with dollars straight from a bank account—as opposed to the majority of marketplaces, which require payment for NFTs in Ether, the cryptocurrency of the Ethereum blockchain.

6 The Future of NFTs for Art and Collectables

As discussed in earlier sections, the NFT art market sits at the crossroads of cutting edge technology (Section 2) and the traditional art market (Section 3). This collision has created a unique digital culture and a digitally realized marketplace (Section 4 and Section 5), results that have the potential to empower artists by adjusting the balance of market power in their favor. We foresee multiple potential paths for the future for the NFT art market. The first would empower artists with unprecedented control of the sale and resale of their work, facilitate the creation of high-tech work, and grant access to profits in previously impossible ways. The other is a picture of dysfunction: bots snapping up pieces and excluding most attempted market participants, artists unable to execute more control over the sale of their work due to lack of technical knowledge, and undetectable art-related crime. The true future of the NFT art market is likely to contain features from both visions, so we discuss elements of both.

Technology	Description	Application to NFT Artwork	Current Example	Future Potential
Tokenization	The conversion of assets into digital units that can be bought and sold.	New or existing works of art are created as digital tokens, NFTs, which can be bought and sold.	Artists have released tokens that can be redeemed for specific works of art.	Traditional art museums could tokenize famous physical works and sell NFT prints.
Decentralized Identity	Decentralized identity systems allow users to gather and manage their own credentials under the banner of self-created decentralized identifiers (DIDs).	NFT distribution and NFT appearance or evolution can be conditioned on the personal characteristics or credentials of buyers.	An artist could require identity verification to participate in sales of their work and ensure that each person can only buy one piece to maximize the number of collectors.	NFT artwork could be created to reflect characteristics of the buyer and their behavior.
Blockchains	A blockchain is a robust, decentralized, publicly auditable ledger of all transactions across a peer-to-peer network. It can support self-executing programs called smart contracts.	Each bid, sale, and resale of an NFT artwork is publicly viewable. Artists can set rules for the sale and resale of their work using smart contracts, which open new possibilities for royalties.	A potential buyer of NFT artwork can easily view its provenance publicly with certainty that it is tamper-proof.	NFT art buyers may pay a higher price if a prominent collector owned the work in the past.
Decentralized Finance (DeFi)	Decentralized finance (DeFi) is a system by which financial products are created on a blockchain network using smart contracts.	DeFi enables new ownership structures for NFT artwork, like ownership of work by groups of investors across borders with practical executions of art funds as decentralized autonomous organizations (DAOs). Ownership can be subject to any desired programmatic form of governance.	A group of investors from different countries who do not know or trust one another can use a smart contract to form a decentralized autonomous organization (DAO) and buy an NFT artwork together. Any investor can sell their portion without impacting the others.	NFT artwork could become the basis of investment vehicles like index funds. Prediction markets for works' value could arise, allowing users to make financial bets about works they do not own.
Oracles	Oracles are authenticated data feeds that relay off-chain data onto blockchains.	Oracles allow NFT artists to incorporate real-time and off-chain data into their work.	Dynamic NFTs, which use oracles to incorporate off chain data, can be used to award an NFT artwork as a prize for in-game performance in a video game.	An NFT artwork of a sword could be used in a video game and the artwork on the blockchain could change as it is used in the game- for example, the artwork of the sword would break if broken in the game.
Trusted Execution Environments (TEEs)	TEEs use special hardware (or software) to perform computation off-chain both privately and with provable correctness.	Trusted hardware allows NFT artists to incorporate secrets into their works. Trusted hardware can also serve as a means by which tasks too computationally intensive for smart contracts can be performed off-chain in a trustworthy way.		NFT artists could design works that incorporate secrets. For example, an NFT could include a labyrinth of which pieces come into view only when explored by a user, while other portions remain hidden. Such secrecy is not possible on blockchains, which are transparent by design.
Machine Learning (ML)	Machine Learning (ML) algorithms are software that plays a role typically assumed by human beings. Machine learning uses computer algorithms that can improve automatically through experience and by the use of data.	Machine learning facilitates computer-generated NFT artwork and art markets with non-human participants.	Algorithms can generate an NFT artwork from a generative model. Algorithms could then price and bid on the piece and a machine learning driven critic could assess its merits.	ML can partially or fully supplant the roles of all art-market participants: artists, buyers, gallerists, and sellers. We can imagine ML-based approaches to generative art, buying, curation, criticism, etc.
Decentralized Storage	Decentralized storage enables robust, permanent storage of data.	Decentralized storage offers an opportunity to archive NFT data with strong assurance of availability and survivability.	NFT art collections can be stored using Filecoin, arweave, or the Graph, giving them archival insurance.	Multi-generation NFT art collections could outlast changes of regime (i.e., political revolutions), traverse national borders with their owners, and see many generations of ownership.

6.1 NFTs and Updated Art-Market Dynamics

The fact that NFTs reside in smart contracts makes it possible for artists to dictate terms of sale throughout the entire lifecycle of an NFT artwork. Artists can in principle set richly detailed policies dictating pricing, sale conditions, and so forth—ranging from restrictions on “flipping,” to anti-hording measures that limit the number of purchases of an artist’s work that a single individual can make. Such additional control could lead to a realignment of responsibilities from roles in the traditional / contemporary art market, shifting responsibilities for promotion, sale, and resale to advantage the artist and reduce the power of intermediaries such as galleries while creating high-tech art jobs. This is stylistically similar to the rise of digital self-publishing tied to the growing adoption of eBooks in the non-blockchain world.

Some novel tools along these lines have already seen realization in NFT marketplaces, such as automated accrual of royalties to artists for resales. Marketplaces themselves provide various tools for artists to manage and promote their work, supplanting some of the traditional services provided by gallerists.

There are other ways in which the dynamics of NFT marketplaces could depart from those of traditional art markets. We enumerate some here.

No-trust relationships between artists and buyers: NFT sales are generally executed via a smart contract. By completing a sale using a smart contract, artists and buyers can set crisply defined, technically enforced sale conditions that today rely on trust-based agreements among artist, gallery, and buyer in traditional art markets. For example, an artist or re-seller can set as a condition the price she expects for a given NFT while a buyer can set as a condition that he receives a work of art verified as legitimate by a pre-defined automated process. (See discussion of provenance below.) The result is a “fair exchange”: The artist is guaranteed to receive the money she is asking for her work while the buyer is guaranteed to receive an authentic work. Intermediation by the smart contract means that no trust is required between the parties: If either side fails to fulfill his / her conditions, the smart contract voids the sale.

Mechanized curation of buyer lists for primary and secondary markets: In traditional art markets today, gallerists and artists typically limit sales to buyers who qualify in some way as responsible custodians of the works they wish to purchase. For example, artists and gallerists often prefer to sell to buyers who will cherish an artist’s work and help promote it. Vetting buyers is typically a manual process, often involving interpersonal interaction. In our discussions with artists, manual curation

of buyers—e.g., to prevent accumulation of NFTs by bots—has carried over into the world of NFTs [122].

The process of vetting NFT buyers, however, can be *mechanized*, i.e., automated, by bringing together the technical properties of smart contracts and decentralized identity. As discussed in Section 2.2, decentralized identity tools enable the creation of trustworthy personal credentials usable within blockchain systems (and can do so in a privacy preserving manner). Using such tools it is possible in principle to automate NFT sale policies such as:

- *Discounts* for established NFT artists;
- “*Fair drops*” of new work (e.g., limiting purchases to one piece per buyer to prevent accumulation by bots);
- *Restricting sales* exclusively to buyers who have previously purchased works of art meeting some criterion (e.g., selling only to buyers who already own works by a given artist or artists).

Dictating forms and conditions of ownership: Artists and dealers tend to be wary of so-called “flippers,” collectors who bought in the primary market only to turn around and resell in the secondary market—as discussed in Section 3.1. This wariness translates into mistrust of new collectors and significant restrictions on *who* has access the best works of art in the primary market. With NFTs, however, smart contracts can instead enforce *how* works are sold or resold. This new capable may enable sellers to overcome mistrust of new collectors and enable greater, more democratized access to artworks.

Smart contracts in fact allow NFT artists to dictate the terms of ownership for their pieces in perpetuity even after they have changed hands to the buyer. For example, an artist who wants to discourage price speculation on her NFTs can enforce a minimum period of ownership of minutes, years, or even for all time and restrict how frequently and to whom the work can be resold.

Dynamic pricing: As an alternative or complement to holding periods, smart contracts can allow artists to dictate sale prices for both primary and secondary markets, e.g., set dynamic pricing conditions. An artist interested in reducing price speculation on an artwork, for example, could allow arbitrary resales, but enforce a price cap. Pricing restrictions can in principle be fairly sophisticated: For example, the maximum (or minimum) sale price for a work could be linked to market indices, such as the average price for an artist’s work or within a genre. Such pricing regimes

could serve the dual function of turning away buyers interested in price speculation and incentivizing individual responsibility on the part of any collector for pricing of the artist’s body of work, as current sales may impact the future value of a body of work.

Innovative royalty schemes: It is common practice in NFT marketplaces for artists to receive certain percentage of the resale value of their works as a royalty—in perpetuity. This is in fact one of the key marketplace innovations introduced by NFTs. For example, DADA.nyc collectibles pays NFT artists a 30% commission for resales of their work [2]. In the traditional art market, *droit de suite*, the “right to follow,” is a covenant that enables artists or their estates to earn a percentage of proceeds from the sale of art in the secondary market. It is currently applicable only in some European jurisdictions and difficult to enforce [3]. With NFTs able to provide royalties from secondary sales, artists in all jurisdictions can now access a revenue stream that extends past the first sale of their work.

Novel royalty schemes are also possible. An example of an existing such scheme is the model used by Eulerbeats. Eulerbeats created a set of NFT artworks with a limited number of copies, “prints,” of the works. Sale of the copies generates a royalty paid to the *owner of the original NFT*. Resale values of Eulerbeats NFTs follow a bonding curve, the relationship between the price and supply where each sale will increase price of future sales. Rather than reselling prints, owners also have the option of sending them to a contract that destroys (“burns”) them and pays a reward for reducing the overall supply [26]. One can imagine even more innovative schemes for royalty and resale arising in future NFT art markets. For example, a collection could be designed where all royalties are awarded by lottery to one randomly selected owner of a piece from that collection, adding a gambling element to the financial rewards of art collection.

“Safe contract” to empower and protect artists: In the world of venture funding, the rise of accelerators with standard terms of agreements has led to the emergence of the “Safe Document,” for non-institutional, angel, or seed investors in a startup. These documents are general-purpose and have been standardized after several rounds of vetting by lawyers, investors and other relevant parties in such transactions [8]. They are widely accepted as an inexpensive way to close an investment in such a way that both parties are reasonably protected. We think that the potential design of a set of standardized smart contracts for the distribution and resale of NFT artworks could similarly protect participants in NFT transactions from the challenges arising in what is today a largely unregulated market. Overtime, a

more ambitious system is perhaps possible, for instance an engine that allows artists to tailor contracts flexibly, but with strong guardrails (e.g., legal enforceability).

Provenance Meets Blockchain Transparency NFTs are issued, stored, and sold on blockchains, which provide publicly-auditable records of all transactions. This means that tamper-proof records of an NFT’s provenance are always available. This record provides a high-trust mechanism to address provenance disputes and any provenance uncertainty, a problem that is rife in existing art markets. See more about traditional art markets in in Section 3.

6.2 NFT Artwork as a Financial Instrument

NFT artwork can be treated as digital wealth, much like cryptocurrency, in that it can be valuable and quickly transferable irrespective of buyer and seller geographies. These features have already led to the use of NFT artworks as collateral for loans [34], financial derivatives [10], and NFT artwork price prediction markets [109]. As a valuable asset, NFT artwork will also spur the growth of related industries, like insurance companies with the technological knowledge to offer NFT artwork insurance for theft or loss and NFT artwork experts to advise wealthy buyers.

Who Should Buy and Own NFTs?: The ability to create, buy, and trade NFTs at present is more open than in traditional art markets. NFT artists must only have access to a cryptocurrency wallet application, make an account on a platform like Opensea, and be able to pay transaction fees to mint their NFTs. NFT buyers have the same technical requirements. Although access to traditional fine art markets is limited by gallerists and auction houses, which often exclude unknown buyers or those with a reputation for reselling works, the traditional art market is still notorious for money laundering [110]. Without gate-keeping by gallerists and auction houses, anyone with the resources can participate in the NFT market. This openness could lead to a more democratized art market, however, it raises regulatory concerns.

Identity verification standards to purchase and trade NFTs are not universally enforced. In the broader cryptocurrency ecosystem, identity verification and enforcement against money laundering and the financing of terrorism has been left to exchanges, the companies that allow trading of cryptocurrency for government-issued currencies and vice versa. With identity verification completed as a separate step at the discretion of private companies for many cryptocurrency-to-cryptocurrency transactions, legal enforcement against criminal users can be challenging. As NFTs embody large amounts of value, their use for illicit purposes as an alternate form of

digital wealth to cryptocurrency will raise challenges for national financial law enforcement agencies. One potential solution would be to require identity verification using a centralized or decentralized identity system before an individual can interact with NFT trading platforms. As with know-your-customer (KYC) / anti-money-laundering (AML) systems in the traditional financial system, sanctions lists could arise for users who have engaged in criminal activity.

New Financial Instruments with NFT Artworks: An NFT artwork can be easily fractionalized and owned by groups of collectors using a smart contract that custodies the work and parcels out ownership shares. These ownership shares can be publicly viewed, ownership can be proven, and shares can be resold or further fractionalized. Buyers of NFTs have in some cases achieved massive and rapid price appreciation by fractionalizing ownership and selling shares. (Their approach is analogous to real estate developers who buy parcels of land and carve them into lots.) For example, DOGE, an NFT of an image of a dog, sold for a total of 11,000 ETH once fractionalized after its initial purchase for 1,696.9 ETH [130]. Protection against fractionalization using price caps by artists hoping to discourage price speculation for their work can be found in Section 6.1.

Art funds in traditional markets have not become popular. In contrast, there has been a significant growth of funds where investors buy re-sellable shares of a selection of NFTs from successful collections. These funds are roughly like index funds, allowing investment in a portfolio of NFT artwork that is broadly representative of a segment of the NFT market. While the reason for the popularity of such funds in the NFT community is unclear, it no doubt helps that NFT artworks can be bought and sold quickly, without the hassle of transporting and securing valuable physical objects.

NFT funds typically operate in a decentralized manner as DAOs (see Section 5.2). DAOs enable funds with no managers, only stakeholders, and could revolutionize collective ownership of fine art [13]. Similarly, one could imagine NFT art museums operating as DAOs, with patrons guiding acquisitions and exhibitions.

6.3 NFT Artwork at the Cutting Edge of Technology

NFTs themselves and the markets created to buy and sell them are new and do not carry the centuries of tradition, norms, legal frameworks, and community practices that surround the traditional art market. NFT artworks can rapidly benefit from innovations in their creation and purchase and sale. They may also emerge as a new frontier for tech-savvy criminals.

Monetization of influence: With more transparent ownership and faster sales cycles comes the opportunity for well known collectors and other high-profile individuals to monetize their reputations through implicit or explicit endorsements. While reputational monetization isn't a new phenomenon, NFTs ecosystems can realize it in a faster and more direct way that, e.g., product endorsements in advertisements. All offers submitted for an NFT can be seen publicly, and thus even interest by a high-profile individual is a matter of permanent public record. As a result, prestige may attach to pieces that known collectors and influencers have tried to acquire—even if they didn't ultimately buy them. Provenance in the sense of ownership is an important factor in price-setting in traditional art markets (see Section 3). But in the traditional art markets, unsuccessful bids are typically not publicly recorded and works do not change hands with the rapidity of many NFTs.

In consequence, one can imagine artists inviting notable collectors to participate in their drops or bid on their NFTs, or even resorting to bribery of influencers if their participation successfully stimulates interest. Bots can automate bidding, enabling far-reaching provenance manipulation. Influence peddling could be very lucrative in NFT markets unless there is sufficient community backlash to discourage the practice.

New forms of crime and forgery: A technologically savvy hacker could forge NFT artworks in ways previously infeasible for fine art.

For example, a hacker might seek to compromise an artist's private key(s) (the secrets used to mint NFTs in her/his name) or passwords for an NFT platform. The hacker could then use machine learning techniques to generate NFT artworks that are difficult for users to distinguish visually from legitimate works by the artist. The result would be stylistically plausible fakes with authentic-looking pedigrees. The rapid pace of NFT markets, moreover, would enable the hacker to sell off these fakes quickly through the victimized artist's usual sales channels. It would be challenging for an artist to cause the resulting funds to be confiscated or otherwise obtain redress, as the hackers' funds would take the form of cryptocurrency.

While such hacks have not yet occurred to the best of our knowledge, the right preconditions are already in place. Online accounts of famous users are regularly hacked, as happened in 2020 with various high-profile Twitter accounts [114], and generation of digital art via machine learning is making steady advances.

To protect against such pedigree-forgery attacks, NFT artists need to maintain good cybersecurity practices—the same practices needed to protect users' cryptocurrency. Techniques proposed for protection against cryptocurrency thefts could also help minimize the risk of NFT forgery. One example are *covenants* [125], which

would automatically enforce a delay on an artist’s NFT releases, i.e., minting activity, leaving open the option of the artist cancelling the release in the case that theft of a key or another mishap occurs.

The Bot Art Market: A future is conceivable in which machines shape or even dictate tastes in art markets. Machine learning can be used to create NFT artwork and also to purchase it. Thus the principles of taste that govern the desirability of NFTs may deviate from human taste. While this seems to be a futurist prediction, machine learning is already used to generate NFT artwork. For instance, an algorithm called Botto generates art and each week mints a piece as an NFT based on votes from the Botto community [14]. The Gan Apes [29], a series of NFT artworks, are created by feeding existing NFT artworks called the Bored Apes into a machine learning system called a Generative Adversarial Network (GAN). What is created is an image generally recognizable as a version of a Bored Ape, but differing in form, color, and style.

Machine learning has another role to play in NFT markets as well. NFTs more closely resemble traditional financial instruments than traditional works of fine arts, as discussed in Section 6.2. Financial trading firms commonly use machine learning to craft trading strategies. NFT trading is a natural application of machine learning algorithms, one that will inevitably arise if it hasn’t already. An interesting twist, however, is that such algorithms may take as input not just data on market dynamics, but also characterization of the style of NFTs, i.e., trade in part based on NFT *styles*.

Beyond prediction of NFT market movements to devise profitable strategies, machine learning algorithms could also discover ways to *manipulating* art markets, i.e., strategies to influence the trading behavior of market participants. The result would be use of machine learning algorithms not just to predict market movements, but to influence them for profit.

Evolving Dynamic NFTs Oracles allow blockchains to interact with off-chain data in a trustworthy way (see Section 2). Through use of oracles, physical and digital world occurrences can be incorporated into NFT artworks. For example, a user could purchase an NFT artwork for use in in a video game. Depending what happens to that work in the video game—anything from theft to additional ornamentation added in collaboration with an artist—the actual NFT of the artwork could change on-chain. Additionally, oracles allow real-time data to be incorporated into NFT artwork. For example, an artist could design a work with a character whose motion mirrors the real-time dancing of a performing ballerina in the physical world. Some current implementations of dynamic NFTs use verifiable randomness

to determine their characteristics or can use off chain records to determine NFT ownership, for instance an NFT that changes owner based on the winner of a game [1]. As oracles and their involvement in the creation of NFTs mature, NFT artwork can include increasingly rich information. These more mature NFTs may gain traction as avatars, decorative art, and objects in the metaverse, the blending of the digital and physical world.

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A Further Details on Blockchains

This appendix provides more information for readers interested in understanding blockchain systems in further depth. We first describe two important building blocks, *cryptographic keys* (covered briefly in Section 2.1) and *digital signatures*. We then present a conceptual blockchain and use it to illustrate the basic mechanics of a blockchain system by describing the processing of several example transactions.

Cryptographic keys: To participate in a blockchain system, a user randomly generates on her computing device a pair of keys: a *private key*, which she keeps secret, often denoted by \mathbf{sk} and a corresponding *public key*, often denoted by \mathbf{pk} . These keys are quite short: 32 characters (specifically, hexadecimal digits) in most systems today.

The public key serves as the user’s (pseudonymous) identifier on a blockchain. From it is derived the *account number* (or equivalent) of the user. The public key authenticates the user’s transactions (as we explain below). The private key serves to control the user’s assets. It acts roughly like a password, but with more sophisticated functionality, as we explain shortly.

The decentralization of blockchain systems means that possession of a private key confers complete control of assets in the associated account. If a user loses her key, however—or has it stolen by a hacker—there is no authority that can help her recover it. For example, if a user owns cryptocurrency in an account for which she has lost the private key, she cannot spend the cryptocurrency.

Digital signatures: A private key controls digital assets on a blockchain by means of *digital signatures*. A digital signature is a cryptographic protocol for authenticating messages.⁶ A user can apply her private key \mathbf{sk} to a *message* m —any desired string of characters of any length—to yield a digital signature s . This signature s is typically around 512 bits in length.

Anyone with knowledge of the user’s public key \mathbf{pk} —which is represented on the blockchain—can verify that a signature s on a message m was indeed generated using the private key \mathbf{sk} . The essential property of digital signature schemes is that *is infeasible for anyone lacking knowledge of \mathbf{sk} to produce a valid signature s* . In other words, digital signatures *cannot be forged*.

Digital signatures are the means by which users control their assets on blockchains. To transfer ownership of an asset, the asset holder generates a digital signature s on

⁶Note here that while cryptographic in nature, digital signatures and blockchains in general do not involve any *encryption*: There are no secret messages in blockchain systems.

a message m that authorizes the transfer of the asset to another user. Because the user's public key pk is represented on the blockchain, *everyone* can verify that the transaction is valid.

Conceptual Blockchain

To illustrate how digital signatures serve to authorize transactions, Fig. 9 depicts a conceptual blockchain with three accumulated transactions that send value and an NFT among accounts owned by Alice (A), Bob (B), and Carol (C).

Transactions m_1 , m_2 , and m_3 are posted to the blockchain in that order over time. Their effect is to move assets among accounts belonging to Alice (A), Bob (B), and Carol (C). Associated with each account are a private key and public key. Thus, for example, Alice has private key sk_A , which she keeps secret, and public key pk_A that is associated with her account A on the blockchain; Bob and Carol hold analogous keys.

The notation 'SIG(X , msg)' in Fig. 9 denotes a digital signature from acct. X (one of A , B , or C) on a message msg. Thus the transaction m_1 represents a signature that Alice generates using her private key sk_A whose validity others can verify using pk_A . The transaction sends \$10 from Alice to Bob.

Balances shown to the right indicate changes over time resulting from assets moved as a result of transactions posted on the blockchain. To determine the current state of asset ownership by all account holders, anyone can scan the full blockchain and tally the asset transfers resulting from validly signed transaction messages.

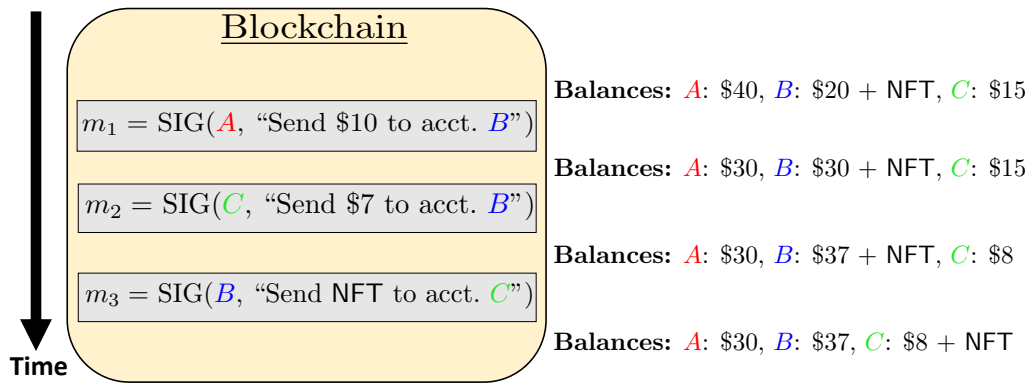


Figure 9: Conceptual blockchain example. A sequence of three transactions (m_1 , m_2 and m_3) moves assets among accounts belonging to Alice (A), Bob (B), and Carol (C).