Characterizing the OpenSea NFT Marketplace

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ABSTRACT

Non Fungible Tokens (NFTs) are unique digital identifiers used to represent ownership of various cryptoassets such as music, artwork, collectibles, game assets and allow for an unalterable and provable chain of creation and ownership. The market for NFTs exploded in 2021, and much of the public is being exposed to this new digital ownership medium for the first time. While uptake of this new medium is relatively slow, we feel the prospects of blockchain technology are up-and-coming. NFTs are still largely misunderstood by the wider community, and as such, this provides a fascinating opportunity to explore the NFT marketplace in greater depth. We analyzed sales data from OpenSea - the NFT marketplace with the most extensive user base and sales volume. Our study considered 5.25 million sales that occurred between January 1, 2019, and December 31, 2021. We first lead by presenting an overview of our data collection process and summarizing key statistics of the data set. We examine user behaviour in the market to show that a small subset of heavy-hitters is driving massive growth. Secondly, we review the economic activity within the network to show how these power users drive extreme price volatility within the Art and Collectible categories. Lastly, we review the network of buyers and sellers to show that despite the sparsity that exists in the network, communities of users are forming, and most power users tend to congregate in these structures. These findings shed light on areas of the NFT marketplace that have been relatively unexamined and provide a multi-level analysis of a multi-billion dollar market.

CCS CONCEPTS

• **Applied computing → Media arts**; • **Theory of computation → Cryptographic protocols**.

KEYWORDS

dataset, nft, opensea, blockchain, cryptocurrency, network, ethereum, non fungible token

1 INTRODUCTION

The Ethereum Foundation describes an NFT as allowing us to tokenize any unique asset and have them secured by the Ethereum blockchain. They can "replicate the properties of physical items like scarcity, uniqueness, and proof of ownership" [16]. Interest in - and ownership - of NFTs has grown immensely over the back half of 2021 as individuals start to embrace the underlying blockchain and cryptocurrency technologies used to deliver them. The largest global Crypto exchange - Crypto.com - reports that "The global crypto population has increased by +178% in 2021, rising from 106 million in January to 295 million in December" and that they "expect the number of global crypto owners to reach 1 billion by the end of 2022" [10]. A substantial increase in the cryptocurrency adoption rate has a pronounced flow-through effect, leading to a rise in the number of buyers and sellers of NFTs.

The blockchain and cryptocurrency landscape is quite daunting for the average person to understand in its current state. Cryptocurrency has many concerns slowing down wide-scale adoption - primarily energy usage, security, legality, and a general belief that cryptocurrency is some scam. That being said, many feel that numerous current-state processes can be improved upon by leveraging the power that blockchain provides. At present, NFTs are predominantly centred around the ownership and distribution of artwork. However, that is but a small fraction of its practical uses. For example, blockchain and smart contracts have started to pop up when dealing with real estate contracts [8], wills and estate planning [39], movie releases [17], or even as a creative way to do crowd funding as is the case with Crypto Baristas [3].

To date, research into the NFT marketplace has been relatively limited. As it is an emerging platform with many unique elements, much of the prior research has been focused on more minor yet critical aspects of the market [20, 42]. Most commonly, there have been papers that seek to look at trends specific to a single collection [19] or to link NFT pricing to crypto pricing in general [1, 13]. However, we have found that efforts to examine more comprehensive, longitudinal market views are less prevalent. There is a lack of resources to understand how NFT sales have evolved over the last few years. Our work seeks to provide a comprehensive, end-to-end view of key statistics of NFT sales and shed some light on how this growing market is developing.

Even though the cryptocurrency user base increased to 300 million people by the end of 2021, the average person has limited knowledge of how cryptocurrency or the blockchain work. Governments worldwide have been embracing it, as in El Salvador [36] - or have been calling for an outright ban, as is the case in Russia at the moment [14]. Going even farther still, China has publicly announced a ban on cryptocurrency eight times since 2014 [43]. Products of smart contracts on the blockchain - NFTs - face even

more scrutiny as many are deriding them as being Ponzi schemes or scams.

Our goal is to take a broad approach to analyze NFTs and offer a more generalist approach to understanding the evolution and trends of the market. We performed a longitudinal measurement study of today's largest NFT marketplace - OpenSea [32]. They provide a good representation of the NFT market due to their dominance in sales volumes and the number of traders who frequent their marketplace. OpenSea has recorded $20.37 billion in sales and has over 1.2 million active traders in its network [11]. The following closest network is 950,000 traders but has a volume of just $360 million. We seek to understand user behaviour, economic trends, and network interactions. From this we expect to be able to better understand the market in general, possible future trends, and spur further research into this area.

Data was collected using a combination of the OpenSea API, web scraping, and manual classification to build our final data set. We found that sales trends show a shift from what used to be mainly gaming-related NFTs to becoming heavily focused on art and collectibles. Additionally, the Music category, while new, showed great promise for growth based on strong album release sales for well-established artists. We also found that the NFT network was one of the extremes and was dominated by the top 1% of buyers and sellers, and the majority of sales went to a few select subsets of collections. While we found that there were numerous addresses of buyers who owned just one or two NFTs, we discovered that the buyer-seller network was composed of several rather large communities, which show that buyers tend to stick to a particular category of NFT or that they generally only buy from a small number of different collections.

Our paper makes the following contributions:

- We perform a longitudinal measurement study of the largest NFT marketplace today.
- We present a multi-level analysis and characterization of the NFT marketplace highlighting its salient characteristics.

The rest of the paper is organized as follows: Section 2 gives an overview of the market and defines key terms. Section 3 discusses prior work. Section 4 presents our measurement methodology and dataset overview. Section 5 presents our characterization results of the NFT marketplace relating to user behaviour, economic activity, and network properties. Section 6 concludes the paper.

2 BACKGROUND

While complex under the surface, the NFT marketplace flow can be outlined briefly, as shown in Figure 1. Key processes in the NFT market system are outlined below.

(1) A digital asset is created and its meta-data is held within a smart contract. This is a program that runs on the blockchain and is a grouping of code and state data. These contracts interact with users and "can define rules, as a regular contract, and automatically enforce them via the code. Smart contracts cannot be deleted by default, and interactions with them are irreversible" [28]. This allows Ethereum transactions to do much more than simply storing or sending value.

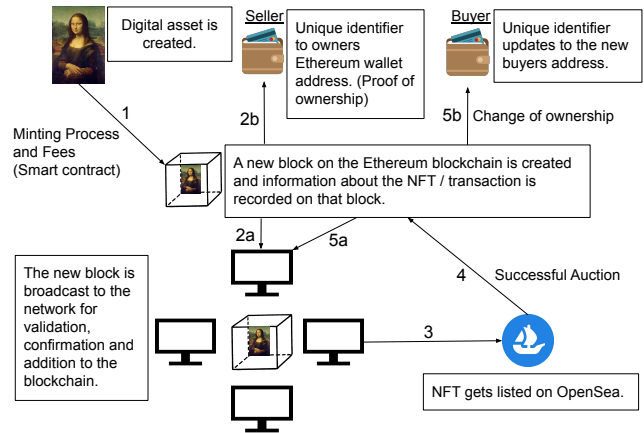(2) The asset is then 'minted' on a blockchain. For our purposes this is the Ethereum (ETH) blockchain, however other

Figure 1: Critical interactions in the NFT marketplace

options do exist. Minting is the term used to describe the process by which a new block is created, validated by the network and ultimately confirmed and added to the blockchain. Each asset has a unique identifier which allows NFT creators to establish a level of scarcity for their assets. Smart contracts also associate a unique Ethereum wallet address of the owner with the NFT.

(3) Once on the blockchain, the NFT can be listed on a compatible Decentralized app (Dapp) such as OpenSea for other users to bid on and purchase.

(4) A sale triggers the process in step 2 to repeat; a new block is created, broadcast, validated, and NFT ownership moves to a new wallet address.

3 RELATED WORK

Existing research on NFTs tends to focus more specifically on the protocols and technology used to support, build, or distribute NFTs themselves. Much of this is centred on two specific issues that have been front of mind, especially as adoption rates climb.

One such area of focus is the environmental impact [26] of NFTs; looking at the greenhouse gas contribution of an Ethereum transaction in its current and proposed future state and how those utilizing the blockchain can best reduce their net effect on the environment. The other major area of focus is on anonymity, malicious trading, and security. As blockchain addresses are anonymous, it opens the door to unethical trading practices such as "wash trading, shill bidding, and bid shielding" [12]. Understanding the potential flaws in the system is critical for future development to ensure a healthy system. One area yet to be explored in depth is the prospect of price-boosting, where a creator drives up the price through artificial demand by selling through a chain of their wallet addresses. This has been topical as the speculative pricing aspect of collectible NFTs creates an opportunity for unethical trades.

Existing papers that seek to provide research on market trends in general more often tend to focus on a small subset of collections or particular sales categories[19, 35] rather than the market as a whole. Given the breadth of collections available to buyers in the current climate, we cannot use the sales trends from a famous collection as

a basis of results for all collections. Sought after collections such as Cryptopunks and Bored Ape Yacht Club [27] are not representative of the market in general.

Furthermore, other empirical papers look to explain price variation spikes [29], or look to establish a linked relationship between the market value of Bitcoin/Ethereum and the price at which creators are listing their NFTs. On the other side of the equation, there has been work that look to NFT creators themselves to understand the human element of the ecosystem [37].

Our focus is to produce an empirical study across a wide range of collections and categories to better understand market trends in general. We seek to understand the power-law behaviour [24] among buyers and sellers and how a small group dominates the market. This is evident once you look at the volume of buyers and sellers represented by just a hand full of communities. Additionally, we examine the long-term pricing trends in the main NFT categories and how the typical NFT has adjusted its price position in recent years. With this, we can gain insights into the quickly evolving NFT landscape and anticipate areas of growth or decline.

4 METHODOLOGY

4.1 Data Collection

We opted to collect sales data from OpenSea, the largest active NFT marketplace. Statistics show that OpenSea has accumulated over $20 billion in trade volume, boasting more than 1.2 million traders [11].

The data set was built using the provided OpenSea API, where we made our queries against the Events endpoint. To make the data collection and validation process more manageable on both us and the platform, we split our queries into smaller segments and used a moving window of Unix timestamps to pull data on all successful OpenSea sales between January 1, 2019 and December 31, 2021. This amounted to a total of 5,252,252 sales records over the three years.

One limitation of the API was that there was no classification of the category of NFT that the sale belonged to. There was no indicator if the NFT fell into Art, Collectible, Music, Trading Card, etc. To label the sales, we web scraped a large number of categories to collection name connections directly from OpenSea's browse pages. This gave us just over 50,000 collection names and their corresponding category on OpenSea. We also performed a manual inspection for the following 1,000 largest collections where web scraping did not provide the data. This involved browsing several assets from each collection on OpenSea's website to make a determination ourselves as to which category of NFT they fall into. For any collections remaining - as well as those with no provided collection name from the API - they were labelled as Uncategorized. In total, we had ten different categories of NFTs tagged as shown in Table 1.

It is worth noting that Music and Photography did not have sales data in the early years. Data for these categories started to appear late in 2020 only, so gaps in 2019 and 2020 are simply from the recent introduction of these categories.

Additionally, there is considerable overlap between the Art and Collectible categories, and these two categories are nearly interchangeable. For example, OpenSea lists CryptoPunks as Art, whereas NonFungible Corporation considers them as Collectibles. Our findings for Art and Collectibles were similar, so this categorical variance is not a significant concern.

The OpenSea API captures the USD price for Ethereum at the time of sale. As such, all prices mentioned in this paper represent the exchange rate at the time of sale.

Some confines that we had on our work are well worth mentioning. Data was gathered directly from the OpenSea API, which, while functional, lacked the detail that could enhance the study. No in-built categorization meant that this had to be done in a hybrid manner with web scraping and manual review, but that opened the process to arbitrary labels or misclassification. All NFTs were on the Ethereum blockchain, and at the time of writing, several additional established blockchains were offering NFTs that are suitable candidates for inclusion into studies. Namely, Solana [38], Tezos [31], and even Bitcoin [40] have embraced NFTs. As more blockchains support smart contracts, their transactions would need to be included.

4.2 Data Overview

Table 1 outlines the breakdown of sales by category and year. Sales volume had a marked increase over two years - growing 41% from 2019 to 2020 and an incredible 3,857% from 2020 to 2021. There were days in November 2021 which had more sales than the entirety of 2019/2020. Aside from domains, every category exhibited considerable year-over-year growth. Music and Photography had modest showings for their first year on the OpeanSea platform. Future analysis on sales trends from 2022 onward should examine if these categories can keep pace with the rest of the market.

Incredibly, collectibles grew by over 10,000% from 2019 to 2021 as buyers started to pay attention to the hype surrounding NFTs and likely took notice of the sale price of the most well-known collections. Most sought-after collections such as Cryptopunks and Bored Ape Yacht Club were selling for hundreds of thousands, if not millions of dollars.

Virtual Worlds - which account for the gaming-based NFTs, were the dominant category in 2019 but have been quickly overtaken by other categories that had more speculative value. That being said, there is an increasing number of top-tier game developers who have announced plans for introducing NFTs into their games. This news has not been met with much enthusiasm [5], but as the concept matures, Virtual Worlds is likely poised to exhibit considerable growth in the coming years. In recent years, "Free-to-play" games with no base price but offer in-game purchases have become immensely popular. Revenue comes from the sale of digital game assets inside the game environment. Developers can earn billions of dollars a year [41] and could make more by cutting out various bank and processing fees by moving directly to the blockchain.

However, speculative buyers were more often than not "starting to show significant resale rates at a loss" as the year went on [9]. As we will soon see in more detail, NFT sales have normalized somewhat heading into 2022. Ethereum hit its all-time high market price on November 9, 2021, and began to experience a serious decline in value around mid-December. This is also when we notice NFT sales volume decrease dramatically.

Table 1: NFT sales by category and year

Category	2019	2020	2021
Art	2,524	10,595	1,132,707
Collectibles	27,395	32,346	2,844,337
Music	-	25	15,254
Photography	-	-	11,499
Domain	8,060	2,461	6,166
Sports	1,106	442	24,380
Trading Cards	2,896	2,880	78,788
Uncategorized	7,923	21,322	484,291
Utility	853	2,589	249,004
Virtual Worlds	39,478	54,578	188,353
Total	90,235	127,238	5,034,779

Table 2: Distinct types by year

Type	2019	2020	2021
Buyers	7,845	16,831	601,183
Sellers	6,771	13,152	303,629
Collections	331	1,139	50,870

Table 3: Summary statistics of price by category

Category	Max	Median	Mean	SD
Art	$8,030,400	$634.09	$2,840.04	$19,596
Collectibles	$3,744,252	$554.88	$1,869.68	$8,299
Music	$339,001	$220.19	$740.78	$4,737
Photography	$160,860	$571.95	$1,742.41	$5,704
Domain	$1,593,900	$204.65	$2,458.92	$17,352
Sports	$152,360	$454.50	$810.78	$2,485
Trading Cards	$1,610,822	$464.81	$2,970.10	$13,287
Uncategorized	$4,988,347	$188.50	$1,635.03	$22,367
Utility	$764,800	$569.33	$1,825.73	$7,779
Virtual Worlds	$5,357,800	$743.27	$2,609.74	$15,141

Table 2 gives a split by year of the distinct counts of buyers, sellers, and collections involved in those sales. The ratio of unique buyers to sellers remained relatively consistent in 2019 and 2020 - 1.16 and 1.28 buyers per seller, respectively - however, in 2021, we see that this has grown by nearly 55% to a 1.98 buyer to seller ratio. Unique collections where at least one sale was made also increased just over 44-fold between 2020 and 2021 to 50,870 distinct collections.

As shown in Table 3, many sales categories featured rather extreme ranges for prices. The standard deviation (SD) for sale price by category shows how extreme prices can range. As a result, we know that the median is a better measure of comparison. Domains had a rather unusually high maximum sales price, which was for an Ethereum Name Service domain - `paradigm.eth`.
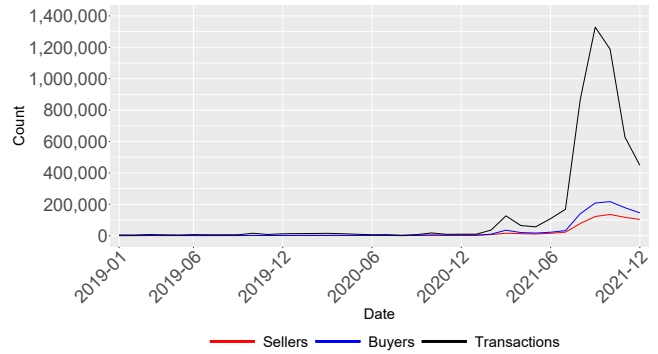
Figure 2: Timeline of buyers, sellers, and transactions

5 CHARACTERIZATION RESULTS

5.1 User Behaviour

In this section, we will review the results of our analysis as they relate to user behaviour. We will look into the trend of how many typical transactions we would expect from buyers and sellers and which category of NFT those purchases may fall into. We will show how the distribution of frequency-rank for buyers, sellers, and collections fits a stretched exponential distribution. Lastly, we will look at how the market follows a Pareto 80-20 ratio.

The latest report released from the NonFungible Corporation noted that "the number of sellers is growing faster than the number of buyers, which may suggest that the conversion of 'new entrants' to become 'NFT Traders' is accelerating" [9]. However, we found that within the OpenSea marketplace, this was not the case. The growth of buyers is outpacing sellers by a rather large margin. From 2020 to 2021, there was an increase in unique buyers of 3,471%, whereas for sellers, they saw an increase of 2,208%.

It is interesting to note that despite the significant increase in NFT transactions in August 2021, the average number of purchases by a typical NFT buyer declines from 2019 to 2021.

In 2019, the average buyer would purchase approximately 5.7 NFTs in any given month. In 2020, this dropped to 4.7 per month, and finally, in 2021, it dips again to 4.2 per month. Much of this could be attributed to the shift in the mix of categories of NFTs which are being purchased each year.

Figure 3 shows the proportion of sales for each category by year. In 2019 we saw that the bulk of sales belongs to the Virtual Words category. However, by 2021 over 80% of all sales fall into the Art and Collectibles category. This supports previous research which noted that "the market volume has been largely dominated by NFTs categorized as Art, which, since then, have contributed 71% of the total transaction volume, followed by Collectible assets accounting for 12%" [30]. Virtual World sales had a higher median sales value of $743.27, while Art and Collectibles were $634.09 and $554.88.

Figures 2 and 6 illustrate how dramatically sales trends differ between 2019-2020 and 2021. Interest in NFTs picked up in 2021. As a result, we decided to look at the subset of January 1, 2021, through December 31, 2021, as it was believed data more or less starts to normalize and be a better representative of typical sales trends.
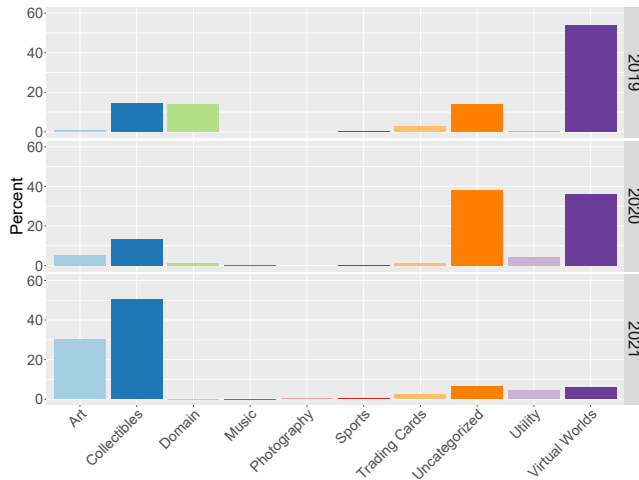
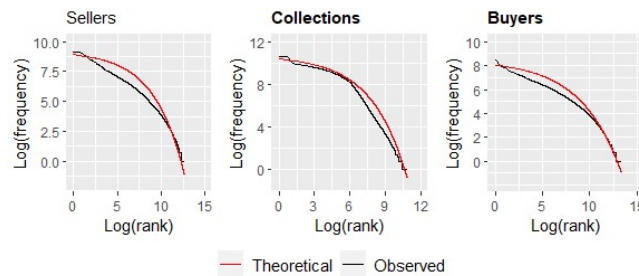**Figure 3: Proportion of sales for each NFT category per year**

Figure 4: Rank-frequency plots of buyers, sellers, and collections

Table 4: Coefficients of fit for Laherrere distribution

Plot	b	n_0
Buyers	0.235	45
Sellers	0.29	100
Collections	0.335	35

Figure 4 shows a log-log plot of the rank versus frequency of buyers, sellers, and collection counts. We analyzed the results against several variations of a power-law fit. The results did not fit that of a Zipf, Mandlebrot, or Lavalette distribution [25]; however, we found that they all seemed to resemble a Laherrere distribution more closely [23, 34] once we analyzed sales trends for 2021.

The distribution is defined as $f(r) = c\,exp(-(\frac{r}{n_0})^b)$ where $f(r)$ is the frequency function, r is the rank, c is a normalizing constant, b is the shape parameter, and n_0 is the scale parameter.

The parameters for our models are outlined in Table 4.

We found that the top 20% of buyers accounted for 79.7% of transactions, whereas the top 20% of sellers accounted for 83.4% of all transactions. However, when looking at the most popular collections, the top 20% of collections accounted for an impressive 97.4% of all transactions. We find that our data follows many real

world graphs of the Internet or Social Media and are heavily right skewed which "demonstrates the existence of (several) high degree hubs" [7].

Of the top-100 collections sold over the three years, 88 were either art or collectibles and amounted to 1,056,746 individuals sales - or 20.2% of all sales analyzed. Virtual Worlds was next with seven collections and 125,154 sales, followed by Utility (4, 51,649) and Domain (1, 13,205).

Of note is that the fourth most popular NFT on OpenSea by sales volume is an asset named 'NFT Yourself' from the 'KINGS OF LEON X YELLOWHEART' collection, which is a limited edition NFT release of a Kings of Leon album. It was listed at 0.35 ETH, which was equivalent to $133.63 at the time. It had 5,790 sales and accounted for nearly 38% of the entire Music category on OpenSea. Sales figures indicate that Kings of Leon managed to bring in almost $2 million in total sales across multiple marketplaces [22]. However, that is nowhere near the record $11.6 million in sales generated by DJ 3LAU with the auction of 33 NFTs [21]. Given that Music is a relatively new category in the NFT world, these could be outliers; however, it shows that there is at least an appetite for new digital distribution methods for music and is a category to watch in the future.

There has been a bandwagon effect where the NFT market has been flooded with countless AI-generated art or collectibles collections. Given that the top 20% of collections account for 97.4% of all transactions, this suggests that many buyers are instead sticking to collections they know or are buying well recognized and backed projects. This also supports the idea that the resale market is starting to exhibit sales at a loss as many smaller collections would not experience the same primary or secondary sales demand.

Despite massive transactional growth, the average number of NFT purchases by an OpenSea user has decreased by 1.5 NFTs per month. The top 20% of buyers and sellers account for 80% of all transactions in the network, with the top 20% of collections making up 97.4% of the sales. The market mix has shifted from a gaming focus into the art and collectible scene as buyers seek to capitalize on the hype for potential profit on the secondary sales market.
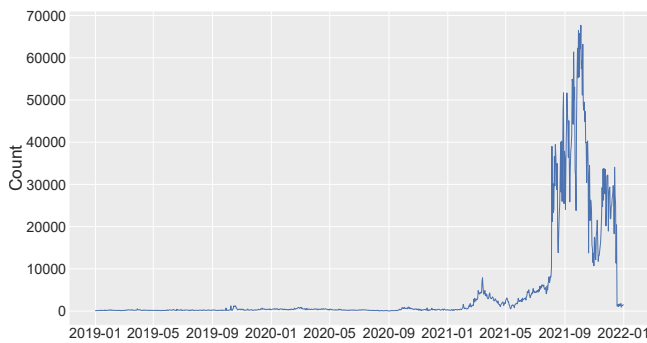
5.2 Economic Activity

What became abundantly clear in our analysis of the NFT marketplace was a system of extremes. There is a common term to describe someone who spends far more than the typical platform user - a heavy hitter [4]. This is no different in the NFT space, as a small group dominates the scene.

Our data's largest NFT heavy hitter is on record for 48,160 purchases - spanning all categories. Interestingly enough, that same account address is listed for zero sales, indicating a longer-term investment strategy. This strategy appears to be rather common as it was noted on another platform analysis that "only 15.72 percent of the NFTs that have been successfully sold on their first auction have been listed for a second auction" [15]. Buyers in the 25th, 50th, and 75th quartiles held 1, 2, and 6 NFTs respectively. Those in the top 1% of buyers held 108 NFTs or greater.

The most notable seller in the network appeared a more modest 9,577 times and made sales only against 2 Collectible collections. Sellers in the 25th, 50th, and 75 quartile had sold 1, 3, or 10 NFTs.
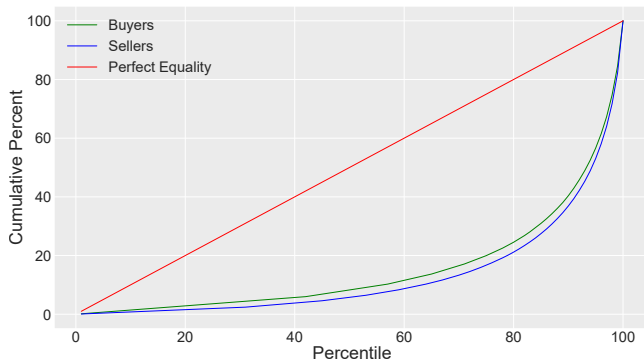
Figure 5: Lorenz curves for buyer and seller percentile by cumulative purchase quantity
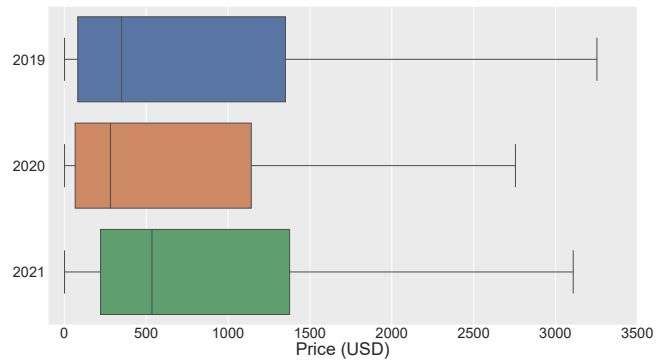

Figure 6: Timeline of daily sales

Figure 7: Box plot of NFT prices by year

Figure 8: Count of the log-price of NFTs over three years

Those in the top 1% of sellers had sales of more than 228 NFTs in our trhee-year period. Figure 5 shows the cumulative percent of purchases made by each percentile of buyers and sellers. This indicates that the distribution of purchases is skewed heavily towards the upper percentile for both buyers and sellers.
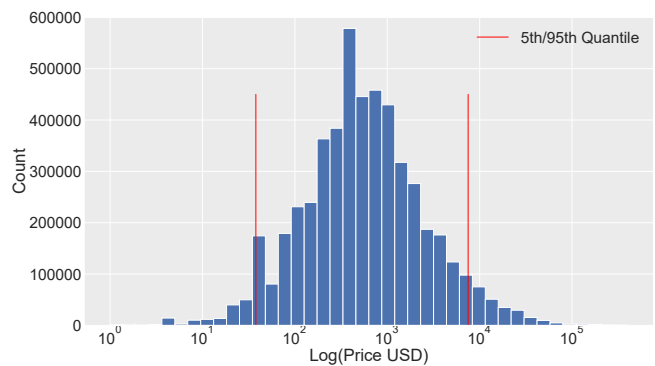
Sales had several distinct periods of sales increase, as is shown in Figure 6. First, a small spike occurred in March 2021, peaking at 7,893 daily sales. The main and global peak was on Oct 4, 2021, with 67,681 sales. Following a dip, there was a slight resurgence through to Dec 14, 2021, with 27,529 sales before the market dropped off and started to average just over 1,000 sales/day from Dec 18 onwards. Data collection ended on December 31, 2021, so it is unknown if this reduced sales capacity continued or to what extent.

When looking at the value of the NFT assets themselves, we found an extremely long tail of values. In our records, the highest value NFT sold for a whopping 2,100 ETH, worth $8,030,862 at the time of sale. The least expensive sale on record was $0.51. Again, if we look at the distribution of prices, we find that the 25th quartile for the cost was $206.25, 50th was $527.85, 75th was $1368.70, and those NFTs which were in the top 1% by sales value were worth upwards of $25,958.11.

Given these extremes, we opted to look at a representation of sales value by year with the outliers removed for clarity. We found that the mean sales price for all three years was reasonably close. The mean NFT sale price for 2019/2020/2021 was $1421/$1456/$1476,

respectively. The median value is markedly higher in 2021, as evidenced by Figure 7, which is expected given the rise in overall sales quantity and general popularity of NFTs for that year [33].

When we started to account for the category of the NFT, we found that the Music and Domain categories tended to have the lowest median value. In contrast, Art, Collectibles, Photography, and Virtual Worlds tended to have the higher median values and the highest extreme values.

With a year-agnostic view, we can see the distribution of sales values as per Figure 8. Ninety-five percent of all sales values fall between $37.79 and $7,501.58, noted by the red bars.

Figure 9 of time series plots of mean pricing by each category revealed interesting trends. Most notably, there was a positive trend in the price over time for Art and Collectibles. The Art category features frequent spikes, coinciding with drops of specific NFT collections that buyers thought were valuable. Buyers of specific collections often get advance notice and priority purchase positioning if the same creators release a new collection. This, in turn, creates a sudden surge of primary sales to get one of the limited NFTs released. This then drives a secondary sales market where opportunistic buyers hope to flip for a quick profit.

We see this same level of pricing volatility across several other categories - most prominently with Domains, Trading Cards, Utility, and Virtual Worlds. Sports typically did not experience much volatility in its pricing, we suspect as it is a relatively small and seemingly undeveloped category. Music had a marked decrease in
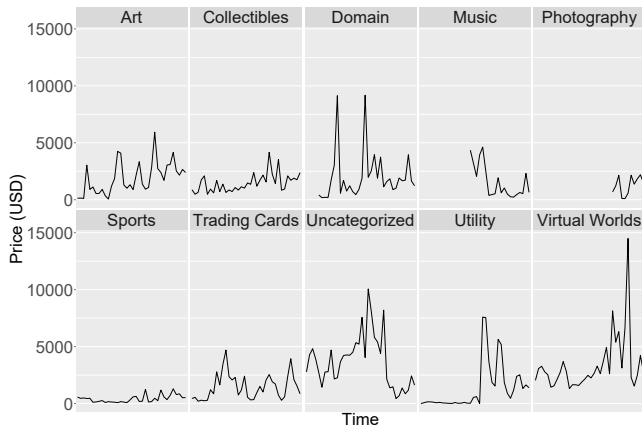
Figure 9: Time series data from 2019-2021 of mean NFT price by category

mean price, but given that nearly 40% of all sales were from a single album sale, it would have an unduly large effect versus the rest of the category.

We attempted to fit letter-value plots [18] to our data to illustrate quantile data better, but with the volume of data points - and the extreme range of values - we found that even this method was unsuitable.

The NFT marketplace is dominated by heavy hitters who spend far more than the typical user. The top 1% of buyers owned more than 108 NFTs, while the top 1% of sellers made at least 228 sales. Those NFTs in the top 1% by sales value were worth upwards of approximately $26,000. However, 95% of all sales fell between $37.79 and $7,501.58. Art and collectibles show a positive trend in their pricing over time and are susceptible to volatile price spikes.

5.3 Network

It was of interest to examine just how buyers and sellers are linked. Given that we have established a top-heavy distribution for the top buyers and sellers, how does that translate into a network-based view? A graph was created where each node represented a buyer or a seller, and an edge connected the nodes if any transaction was done between the two. The network graph was comprised of 637,931 nodes, where each node represents a unique buyer or seller Ethereum wallet address.

The graph was then analyzed using the Louvain algorithm, which extracts community-based structures from networks. This returns a measure known as modularity, a value between -1 and 1 representing the density of links inside communities compared to those between communities [6]. The Louvain algorithm is defined as: $Q = \frac{1}{2m} \sum_{ij} [A_{ij} - \frac{k_i k_j}{2m}] \delta(c_i, c_j)$, where A_{ij} is the weight of the edge between i and j, $k_i = \sum_j A_{ij}$ is the sum of the weights of edges between vertex i, c_i is the community to which vertex i is assigned, δ is 1 if $u = v$ and 0 otherwise, and $m = \frac{1}{2} \sum_{ij} A_{ij}$ [6].

Once run, we had $Q = 0.282$, which suggests a middling level of density of connections, but that is not entirely unexpected given the sheer volume of transactions and the number of buyers who own just a small number of NFTs. Contrast this to looking at the
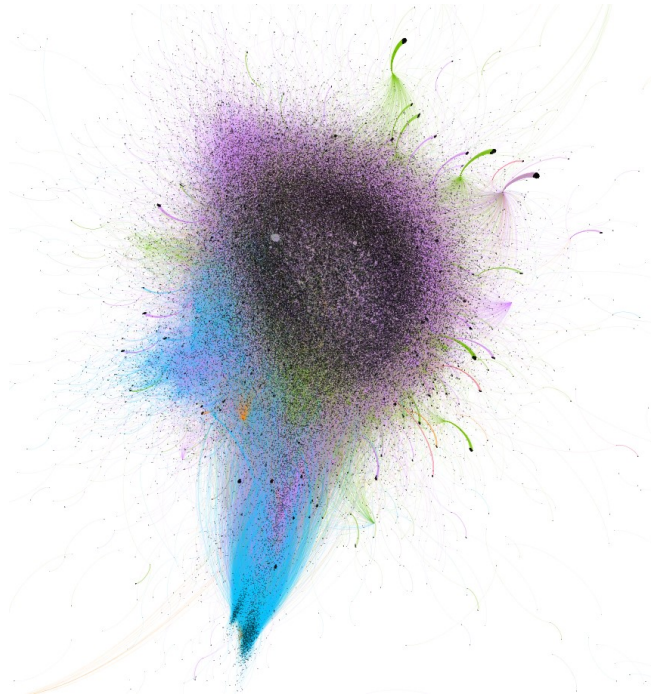
Figure 10: Network graph of buyer and seller connections.

modularity of the music network, which was $Q = 0.915$. As we had noted, essentially a single seller dominated the music category, then this is evidence of just how strongly connected the music community is in its current state.

Figure 10 shows a sample of the buyer and seller network that was analyzed. Each edge represents a transaction between buyers and sellers, whic are the nodes. The colour of the edge represents the category to which the NFT belonged to. The purple edge colouring are NFTs from the Collectibles category, which account for 62.21% of all edge connections. The blue are Virtual Worlds - 5.49%, and green represent Art which make up 24.03% of all edges. A heavy volume of nodes still persist centrally in the graph which speak to the sheer number of smaller, localized transactions that occur between less frequent buyers or sellers.

Furthermore, we found that our complete network graph consisted of 6,959 communities but that the top-10 communities accounted for 86.7% of all buyers or sellers. The largest community in the network was composed of 164,586 nodes (25.8%), and the majority of sales fell within the Art or Collectible categories. A New York Times article noted that the network maps show "that the market for NFT-based art is extremely insular and tightly connected, even by the standards of the art world, especially among owners who buy and sell several times. These network features may help explain the enormous spikes in sales prices for NFT-based art" [2].

Regarding the most frequent degrees, we found that nodes of degrees 1 through 5 comprised 69.9% of all nodes, and the average degree was 13.1. The node with the most significant degree in the network had 26,640 edges.

Table 5: Degree and count of nodes

Degree	%	#
1	38.21%	243,753
2	14.59%	93,074
3	7.92%	50,524
4	5.28%	33,682
5	3.89%	24,815

The next logical step is to review interaction at a within-category type view. Looking at all NFT sales gives us insight into general market interaction, but from the previous analysis, we know that buyers tend to gravitate towards just one or two categories. Some may have obvious overlaps, such as the case with Trading Cards and Sports, so the connection between those categories should be explored. Similarly, future analysis on Virtual Worlds itself could prove insightful as the gaming industry continues to evolve and in-game purchases become the norm.

The network of buyers and sellers is primarily comprised of a community structure as evidenced by ten communities accounting for 86.7% of buyers and sellers. A modularity value of 0.282 speaks to the sparsity outside of these communities. Nearly 70% of user nodes had between 1 and 5 degrees which speak to the level of interactivity of the average user.

6 CONCLUDING REMARKS AND FUTURE DIRECTIONS

OpenSea - and NFT sales in general - have experienced tremendous sales growth from 2019 to 2021. Despite this, the NFT sales market is still in its infancy and has much more room to grow and mature. The global adoption of cryptocurrency will bring in a new wave of NFT enthusiasts, which - along with maturity in blockchain technologies - will further drive market growth.

In this paper, we analyzed 5.25 million sales records over a three-year period which involved ten different categories of NFTs. With this, we looked at user behaviour and how a small subset of buyers, sellers, and collections were driving an overwhelmingly high proportion of the transactions. We also looked at how the sales mix of NFTs based on the category they belong to has evolved quite considerably in just a few years. We analyzed purchase and price history over time, noting the high levels of volatility in sales and both the mean and median pricing of the NFTs themselves. Pricing ranges from as low as $1 to several million dollars, demonstrating how speculative NFTs can be for buyers. Lastly, we looked to network analysis to show that the collective NFT market comprises closely connected communities of buyers and sellers who tend to operate within a specific category of NFT.

These results raise further questions, which would be invaluable areas for us - or others - to continue with in terms of future work. How would a comprehensive review of market trends from within a single category of NFT look, and would it be comparable to the broader market trends? Do other trade networks aside from OpenSea adhere to the same observed sets of behaviours? We feel there are still substantial gaps in the literature regarding NFTs, so we aimed to fill some gaps while stimulating future efforts.

Despite current public sentiment about NFTs, we feel that this is just the beginning of a period of maturity for NFTs and that the prospects for the ability to digitize assets are very strong. Future work should analyze other networks and blockchains as they continue to develop. A more in-depth study of price mechanics would be invaluable, isolating instances of the same NFT being sold in sequence to analyze price patterns and detect fraudulent trades or price boosting.

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