FROM CANVAS TO BLOCKCHAIN: IMPACT OF ROYALTIES ON ART MARKET EFFICIENCY *

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Abstract

Since the advocacy for *droit de suite* in France in the 1890s, policymakers and the public have recognized artworks as intellectual property and sought to grant artists resale royalties—yet encountered heated debates and various logistical obstacles. The emergence of blockchain technology now makes automated royalty collection feasible. We examine the impact of resale royalties on artists' pricing decisions and the overall efficiency of the art market. We build an infinite-horizon model in which an artist sells her artwork in the primary market, after which it can be resold in a sequence of secondary markets. We find that when artwork popularity is public information, royalties—acting as a tax on resales—reduce the artwork's resale value and transaction volume, lowering the artist's profit and leaving all market participants worse off. However, when the artist possesses superior information about artwork popularity compared to buyers, a popular artist may set an inefficiently high price to signal their appeal, which hurts primary market efficiency. In this case, royalties benefit the popular artist by reducing the unpopular artist's incentive to mimic, thereby mitigating price distortion in the primary market. Consequently, the profit of a popular artist first increases and then decreases with the royalty rate, peaking at a unique positive rate. Social welfare may either rise or fall with the royalty rate, depending on whether the reduction in primary-market price distortion outweighs the deadweight loss in resale markets.

Keywords: Art Market, Resale Royalty, Blockchain, NFT, Signaling Game

"One painting, by Robert Rauschenberg, had originally cost Scull $900 in 1958. It sold for $85,000 [in a 1973 auction]. I remember that Rauschenberg was there and he was really incensed, because the artist got nothing out of this."

—"Why is art so expensive?" by Dal Valle (2019) on Vox

1 Introduction

Art is ubiquitous and indispensable to our daily existence. It possesses a remarkable ability to transcend boundaries and connect people from diverse backgrounds, cultures, and experiences. From the subtle design of the San Francisco typeface on iPhones to the captivating visuals in advertisements, artistic expressions surround us. Yet behind these vibrant works, financial difficulty and instability remain constant companions for many artists—even the most prominent ones. This is why, after his work was finally appreciated by the market, Rauschenberg was so vexed by his inability to receive rightful compensation, as hinted in our opening quote.

Rauschenberg's dilemma reflects a longstanding issue faced by many artists. Creating art demands abundant innovation and creativity, rendering each work inherently unique. In this sense, art can be regarded as a form of intellectual property. However, unlike authors, who receive ongoing royalties from book sales, or patent holders, who generate continuous revenue through licensing fees, visual artists face a distinct challenge. In the traditional art market, artworks are subject to a one-time transaction paradigm: once a piece is sold, ownership is entirely transferred to the buyer, leaving the artist with no financial stake in future resales. This lack of recurring revenue poses a significant barrier to financial stability for artists. Consequently, they are incentivized to demand higher prices at the initial sale, which may lead to market inefficiencies. This aligns with the common observation that art galleries often list works with steep price tags, yet experience a limited number of transactions.

While the idea of granting artists resale royalties seems straightforward, its implementation has faced significant legal and logistical barriers. In 1890s, French artist Jean-Louis Forain and others began advocating for *droit de suite*, a legal concept that grants visual artists a royalty payment each time their original artwork is resold in the secondary market. In 1920, France became the first country to enact *droit de suite* into law, followed by several other European nations, culminating in the 2001 EU Directive on Resale Rights[1] which mandated royalty payments for artists upon resales (Stanford, 2003). However, the policy's implementation faced various challenges: UK resisted its adoption, some countries set minimum sale thresholds (e.g., royalties only for sales above 3,000 euros), and debates in the French Parliament (the national bicameral legislature of France) revealed that, in practice, *droit de suite* would drive art resales from Paris to places where it did not apply, like London or New York City. The United States also struggled to enact a national framework. California's 1976 Resale Royalties Act (CRRA), which granted artists a 5% royalty on resales over $1,000, sparked litigation when artists like Chuck Close sued auction houses for noncompliance. In 2011, a federal appeals

[1] An EU directive is a legislative act issued by the European Union (EU) that sets out specific goals for member states to achieve, while allowing each country flexibility in how to implement the laws domestically.

court struck down the CRRA, ruling it conflicted with copyright law (Rub, 2014). Beyond legal hurdles, a fundamental challenge remains: it is very hard, if not impossible, for artists to trace subsequent transactions and ownership of their artworks. These limitations persist in the traditional art market, reinforcing the dominance of the one-time sale model.

Blockchain technology has introduced transformative possibilities for digital ownership and transactions, particularly in creative industries. By leveraging decentralized and transparent ledgers, it enables secure, traceable ownership and innovative smart contracts. This is most evident in the rise of Non-Fungible Tokens (NFTs), which record ownership and transaction history for digital and even physical artworks on blockchains like Ethereum or Solana. The traceability of ownership makes automated royalty collection feasible, ensuring artists retain a stake in their work's ongoing value and providing a sustainable revenue stream beyond the initial sale.

While blockchain technology offers a promising solution to royalty collection, whether to enforce royalties in NFT marketplaces remains a subject of heated debate. Opponents argue that royalties impose additional costs on buyers, potentially hindering the growth of the NFT market. On the other hand, proponents emphasize the importance of royalties in protecting creators' rights and incentivizing the production of unique and valuable NFTs. Table 1 summarizes the recent royalty policies of major NFT marketplaces. We can see that there are various royalty policies across marketplaces and even within the same marketplace (for different contract types), reflecting the ongoing debates and complexities surrounding this issue. Ethereum and Solana, two leading blockchains, keep exploring new standards to facilitate on-chain royalty enforcement.[2] These new technologies allow more NFT marketplaces (such as Magic Eden, OpenSea and Tensor) to introduce tools that enable creators to enforce royalties, as shown in Table 1. As the industry evolves, the debate on royalty policies continues, which underscores the challenge of balancing the interests of artists and buyers in the digital art space—a challenge that mirrors the longstanding struggles in the traditional art market.

How will royalties impact the art market—will they enhance or hurt the market efficiency? Do artists always benefit from the enforcement of royalties? This paper attempts to answer these questions by examining how royalties influence (1) artists' pricing decisions in the initial sales of their artworks, (2) artists' total profit from both the primary and resale markets, and (3) the overall efficiency of the art market. It is worthwhile to note that our intention is not to compare the NFT market with the traditional art market, as there are various factors beyond royalties that differentiate these two markets. Instead, we take the NFT market as a counterfactual of the art market, where the collection of royalties becomes more feasible thanks to blockchain technology, to analyze how royalties impact artists' well-being and the efficiency of the art market as a whole.

We build a game-theoretic model that features a single artist who sells his artwork to buyers in a primary market. The buyer who buys from the artist enjoys the artwork for a period of time before attempting to resell it to another buyer in a secondary market. This process continues with subsequent resales, allowing the artwork to pass from one buyer to

[2]Solana has introduced enforceable royalties through Metaplex's Token Metadata updates and Magic Eden's Open Creator Protocol (OCP), while Ethereum has developed standards like EIP-2981 and ERC721-C, though full enforcement remains a challenge due to workarounds like NFT wrapping.

Table 1: Royalty Policies Across Major NFT Marketplaces

Marketplace	**Supported Chains**	**Market Share**	**Royalty Policy**
Magic Eden	Solana Ethereum Bitcoin Ordinals	36.7%	Allow creators to set and enforce royalties for collections on Solana or certain type of contracts on Etherum. Optional royalties otherwise.
Blur	Ethereum	25.4%	A minimum royalty of 0.5% by default. Creators can choose to enforce royalties, typically ranging from 2.5% to 10%.
OpenSea	Ethereum Polygon Klaytn Base	19.9%	Allow creators to set and enforce royalties for collections on OpenSea Studio or certain types of smart contracts. Optional royalties otherwise.
Tensor	Solana	7.15%	Enforces full royalties on collections designated as such. For other collections, royalties are optional and at the buyer's discretion.
CryptoPunks	Ethereum	5.63%	No creator royalties are enforced on secondary sales.
OKX	Ethereum BNB Chain others	2.41%	Allows creators to set and enforce royalties provided the collection is exclusively traded on OKX.
X2Y2	Ethereum	1.19%	Initially made royalties optional, leading to community pushback. Subsequently, X2Y2 reinstated mandatory royalties for all collections sold on its platform.

Note. Market share data source: CoinGecko (as of August 2024). We collect major marketplaces' most recent royalty policies we can find. The sources of information are as follows. Magic Eden: https://www.coindesk.com/web3/2022/12/01/magic-eden-launches-protocol-to-enforce-creator-royalties; https://help.magiceden.io/en/articles/8995581-enforced-royalties-for-erc721c-collections-on-magic-eden-s-evm-platform. Blur: https://www.nftculture.com/nft-news/blur-and-opensea-royalty-challenges/. OpenSea: https://support.opensea.io/en/articles/8867026-how-do-i-set-creator-earnings-on-opensea. Tensor: https://docs.tensor.trade/trade/fees-and-royalties. OKX: https://www.okx.com/en-us/help/okx-web3-wallet-partnerships-faq. CryptoPunks: https://www.voguebusiness.com/technology/without-royalties-wheres-the-money-in-nfts. X2Y2: https://www.coindesk.com/web3/2022/11/18/nft-marketplace-x2y2-will-enforce-creator-royalties-after-pushback.

another. By modeling both the primary and secondary markets, we enable the artist to generate revenue from both the initial sales and potential royalties from subsequent resales. Instead of considering only one resale market using a two-period model, we model a series of resales so that each buyer can buy, enjoy, and resell the artwork. This is crucial as the artwork serves as both a form of consumption and investment for buyers, where the investment value for buyers comes from their resale profit. We assume that the value of the artwork to a buyer can be decomposed as a private value based on her idiosyncratic preference and a common value, which can be considered as the popularity of the artwork among all buyers in the market. Buyers expect a higher resale price of the artwork when the common value is higher.

In the primary market, each buyer knows how much she likes an artwork given that buyers can examine almost all aspects of an artwork before making a purchase, but she does not know how much of her fondness is idiosyncratic to herself and how much of it is commonly shared by all other buyers. We assume that the artist has superior information on the common value of his artwork than each individual buyer in the primary market. This is a reasonable assumption to make for both traditional and NFT artworks, as we elaborate below.

In the traditional art market, artists are often represented by art galleries or dealers who possess more comprehensive information about the artworks' market appeal than individual buyers.[3] Beyond their domain expertise and knowledge, artists—assisted by their collaborating galleries—can also assess the popularity of their artwork by engaging with potential buyers, observing foot traffic, and tracking inquiries. This information asymmetry has long been recognized (Beckert and Rössel 2013): "Buyers of contemporary art face a problem of fundamental uncertainty, because what passes as quality is difficult to determine, and buyers can hardly estimate how a specific piece of art will perform as an investment [$\cdots$] the value of an artwork or artist originates in an intersubjective process of assessment and conferring of reputation by experts in the art field, such as gallery owners, curators, critics, art dealers, journalists, and collectors."

In NFT marketplaces, artists (NFT creators) also possess superior insight into the popularity of their artworks compared to individual buyers. Creators have access to real-time analytics, including minting rates, secondary sales volume, and community engagement metrics, which allow them to assess demand more accurately. Moreover, NFT creators typically engage directly with their audience through social media and other digital platforms, giving them firsthand feedback and gauging interest levels, which can be predictive of market success. They may also have insider knowledge about upcoming collaborations that could affect the common value of their artworks. Additionally, seasoned creators develop an acute awareness of market trends within the NFT space, further enhancing their ability to estimate the reception of their works. These factors collectively contribute to why NFT creators might have a superior understanding of their artwork's potential popularity in comparison to individual buyers, who can only rely on incomplete public data and may lack access to such comprehensive insights.

Artists' information edge may gradually diminish over time as their artwork gains more exposure in the resale markets. The popularity of the artwork becomes increasingly evident to the public as it is reviewed, critiqued, and resold in secondary markets. We simplify this process by assuming that the artwork's popularity is the artist's private information only in the primary market and becomes common knowledge in all subsequent secondary markets. Besides the incomplete information setting described above, we also consider an alternative information environment where the popularity of the artwork is public information in both the primary and secondary markets. This can be true when, for instance, the artist is very well-known and all of his artworks are highly valued on the market. The complete information case also serves as a benchmark for the incomplete information case, enabling us to understand how the impact of royalties may vary with the information structure.

In the complete information case, we find that the existence of royalties and an increased royalty rate in the market lead to a decrease in the equilibrium prices and transaction volume for both the primary and secondary markets. Consequently, the artist, buyers, and society as a whole all get worse off due to the introduction of royalties. The driving force behind this surprising result is the strategic reactions of buyers towards royalties. Specifically, royalties act as

[3] We do not explicitly model art galleries, who are essentially assumed to be integrated with the artist in our model. An artist usually signs a consignment agreement with one or several art galleries, who are responsible for marketing, exhibiting, and selling the artist's works but do not purchase them upfront. When a piece sells, the gallery takes a commission (usually 40-50% of the sale price).

a tax in the secondary markets, resulting in reduced transaction prices and volume. Anticipating a lower resale value, buyers exhibit a decreased willingness-to-pay in the primary market, which in turn drives down the initial sale price. This effect is so strong that it dominates the additional income gained by the artist through royalties, ultimately causing the artist's welfare to deteriorate. Given that both the artist and buyers experience a decline in welfare, the overall social welfare is diminished with the implementation of royalties.

In the incomplete information case, we assume two types of the artwork—popular or unpopular—and the type is only known to the artist. Because the artist is assumed to sell only one artwork, we can consider the popularity of the artwork and the artist as interchangeable. The equilibrium outcome for the resale markets is the same as that under complete information, because the popularity information becomes common knowledge in resale markets. In the primary market, the artist can use the price to signal the popularity of his artwork. We show that no pooling equilibrium exists, and there exists a unique separating equilibrium where the popular artwork commands a higher price than the unpopular one. The key driving force is that compared to the popular artist, a higher price leads to a larger demand loss for the unpopular artist, which discourages him from mimicking the popular one. In particular, when the difference in common values between the popular and unpopular artworks is relatively large, the unpopular artist has no incentive to mimic even if the popular artist sets the optimal price as under complete information. Hence, separation is achieved without any price distortion, and we call it the *Costless Separating equilibrium*. When the difference in common values between the two types of artworks is relatively small, the popular artist has to set an inefficiently high price to prevent the unpopular artist from mimicking, and we call this case the *Costly Separating equilibrium*. The price distortion hurts the transaction volume and the profit of the popular artist.

We investigate the impact of royalties on market outcomes under incomplete information. Existence of royalties and higher royalty rates increase the likelihood of a Costless Separating equilibrium and reduce price distortion in the Costly Separating equilibrium. This occurs for two reasons: first, higher royalties diminish buyers' resale value, reducing the unpopular artist's incentive to mimic the popular artist; second, high royalties also make demand loss more costly for the unpopular artist because of the royalty income. Both factors make the popular artist easier to separate and less likely to deviate from the optimal price, or deviate to a lesser extent. Regarding profits, the popular artist's earnings follow an inverse U-shape relationship with the royalty rate due to two conflicting effects: the reduced primary-market price distortion and the diminished resale value. Thus, there exists a unique positive royalty rate that maximizes the popular artist's profit. The unpopular artist's profit consistently declines. The effect on social welfare varies: for popular artworks, royalties may increase or decrease welfare depending on whether reduced price distortion outweighs resale deadweight loss, while for unpopular artworks, welfare unambiguously declines.

We examine several extensions of the main model: endogenizing the royalty rate as the artist's decision (Section 5.1), allowing infinite resale opportunities (Section 5.2), introducing salvage value for unsold artwork (Section 5.3), modeling the primary-market buyer as an opinion leader (Section 5.4), and analyzing fluctuating popularity over time (Section 5.5). These extensions explore robustness and additional market dynamics while maintaining the core framework.

Our findings provide important insights for art markets. We show that if there is no information asymmetry between artists and buyers, enforcing royalties will lower the resale value and transaction volume of artworks, hurt artists' profit, and make everyone in the market worse off. If artists have better information about the popularity of their artworks than the buyer in the primary market and the popularity information is revealed in resale markets, royalties will lower the price distortion of the popular artworks, and a moderate royalty rate can increase the profitability of popular artists. If the popularity information is never revealed but buyers in all resale markets adopt the belief of the buyer in the primary market, a higher royalty rate always hurts artists. Unpopular artworks do not benefit from the existence of royalties. The total transaction volume and the total social welfare may increase or decrease with royalties. When the collection of royalties becomes feasible with the technology of blockchain, art marketplaces may decide whether to enforce royalties based on their assessment of the information environment as well as the proportion of popular and unpopular artists.

1.1 Contributions to Literature

The art market is a significant economic sector, valued at $67.8 billion in 2022;[4] yet, it is understudied in academic research. Previous studies have shown that the rate of return on art investments is generally lower than that of traditional financial assets (Baumol, 1986; Pesando, 1993; Goetzmann, 1993; Mei and Moses, 2002; Renneboog and Spaenjers, 2013). Existing works have also explored various determinants of art prices, including equity capital market and income inequality (Goetzmann et al., 2011), artists' gender (Cameron et al., 2019), conspicuous consumption utility (Mandel, 2009), art market sentiment (Renneboog and Spaenjers, 2013), and investor's expectations (Penasse and Renneboog, 2022). Existing research has investigated factors influencing the sale rates of artworks, such as price shocks (Ashenfelter and Graddy, 2011) and provenance information (Li et al., 2022). Lovo and Spaenjers (2018) characterized the market equilibrium of an art-trading economy with idiosyncratic buyer valuations and stochastic macroeconomic conditions. Whitaker and Kräussl (2020) conducted counterfactual analyses, showing that artists may benefit from retaining fractional equity of their artworks by forgoing some payment in the initial sales. More relatedly, Kirstein and Schmidtchen (2001) and Stanford (2003) analyze the economic implications of droit de suite following the 2001 EU Directive and the debate in Australia, respectively. Through theoretical and empirical analyses, both papers conclude that while the policy aims to support artists by granting them a share of secondary market sales, its economic benefits are limited——primarily favoring established artists while creating market inefficiencies like reduced resale activity and misaligned interests between artists and galleries. Rub (2014) is a legal commentary discussing American Royalties Too (ART) Act of 2014, a proposed U.S. bill seeking to establish droit de suite, and echoes similar arguments about the policy's shortcomings. Our paper differs from these works in that we consider price as a signaling device in an incomplete information market of artworks, and shows that royalties may improve market efficiency by reducing price distortion. As far as

[4] https://www.artbasel.com/stories/key-findings-art-market-report-2023?lang=en

we know, our study is the first to demonstrate that artists may use price as a device to signal the popularity of their artworks, and the first to study how the introduction of royalties can influence artists' pricing decisions and the overall efficiency of the art market, assuming the feasibility of royalty collection.

This paper is related to the literature on secondary markets. Existing works highlight a critical tension between the cannibalization risks that secondary markets pose to the primary market and the profitability opportunities they create (e.g., Rust 1986; Hendel and Lizzeri 1999; Chen et al. 2013) and propose strategies to mitigate this type of tension, such as buying-back (Purohit and Staelin, 1994) and trade-in policy (Rao et al., 2009). Shulman and Coughlan (2007) argue that, under certain conditions, secondary markets can complement primary markets, enabling firms to profitably expand their consumer base and target price-sensitive segments. Desai and Purohit (1998) illustrate how leasing can offer firms a way to maintain control over product lifecycles while balancing the benefits of resale opportunities against the risk of cannibalization. Kuksov and Liao (2023) show that an intermediate level of restriction on resellers can benefit the firm by encouraging early purchase. On the empirical front, secondary markets are shown to improve economic efficiency, such as through the redistribution of used goods in automotive markets (Clerides, 2008), the efficient allocation of tickets in resale markets (Sweeting, 2012) and increasing the value of purchasing tickets (Lewis et al., 2019). However, they can also influence consumer behavior, with forward-looking buyers factoring resale opportunities into their purchasing decisions (Chevalier and Goolsbee, 2009) and electronic resale markets sometimes reducing primary market profits (Ghose et al., 2005). These works collectively emphasize that consumers are forward-looking and, when secondary sales are possible, they factor the potential resale value of products into their purchase decisions. This aligns with our model assumption and serves as a key driving force behind our results.

Our paper also contributes to the literature on NFTs. Existing research on NFTs primarily focuses on their features as a financial asset, including the risk and return of NFTs (Kong and Lin, 2021; Mazur, 2021), the development and interrelations across NFT markets (Ante, 2021; Nadini et al., 2021; Umar et al., 2022a), the diversification benefits of NFTs (Aharon and Demir, 2022; Ante, 2022; Borri et al., 2022; Dowling, 2022; Karim et al., 2022; Ko et al., 2022; Umar et al., 2022b; Yousaf and Yarovaya, 2022), and the presence of bubbles in NFT and DeFi (Decentralized Finance) markets (Maouchi et al., 2022; Wang et al., 2022). Baals et al. (2022) provide a comprehensive summary of existing research on the financial economics of NFTs. Other studies have explored questions such as the impact of NFTs on the prices of physical counterparts (Kanellopoulos et al., 2021), and the quantification of suspicious behavior in NFT markets (von Wachter et al., 2022). The existing research studying the pricing behavior of NFT creators or the design of NFT marketplaces, particularly regarding NFT royalties, is limited. We only noticed three papers studying this topic. Falk et al. (2024) empirically demonstrates that royalties are widely existing and enforced in major NFT marketplaces (LooksRare, OpenSea, and X2Y2). They also theoretically show that royalties can benefit creators by enabling them to utilize speculators' information advantage to extract future buyers' surplus. Using data from a leading NFT marketplace, Rarible, Tunc et al. (2024) find that higher royalty rates lead to lower resale prices in the primary market, which is consistent with our theoretical prediction, while they explain it as a delayed gratification effect. A contemporaneous working paper, Yang et al. (2023), explores the potential for royalty fees to serve as a signal, and evaluate the influence of various royalty policies. In our paper, price is the key signaling device, although we also consider royalty rate as a signaling device in one of the extensions. The focus of our paper is to study how the existence and magnitude of royalties affect artists' pricing strategies and social welfare.

Methodologically, our paper contributes to the literature on price as a signal of quality (Wolinsky, 1983; Milgrom and Roberts, 1986; Bagwell and Riordan, 1991), and our paper is also related to the broader literature on signaling. Existing works have studied various signaling devices of product quality, such as advertising (Kihlstrom and Riordan, 1984; Mayzlin and Shin, 2011), warranties (Lutz, 1989), money-back guarantee (Moorthy and Srinivasan, 1995), and brand extension (Wernerfelt, 1988; Cabral, 2000; Moorthy, 2012), among others. More recently, Wu and Geylani (2020) argue that advertising statements can serve as a signal of quality under strict regulations. Wu et al. (2022) show how the opaqueness level of native advertising can signal the publisher's quality under regulation. Chen and Liu (2022) demonstrate that in the presence of ad blocking, advertising spending can signal product quality. Xu and Dukes (2019, 2022) show that product line design and personalized pricing can signal the firm's superior knowledge over consumers. Dai and Singh (2020) find that medical experts may signal their diagnostic ability by the deliberate avoidance of medical tests. Our paper enriches this stream of literature by modeling how price signals product popularity in the art market with information asymmetry.

Compared to the existing signaling literature, our paper has two modeling innovations. The first is on the information structure. Existing works mostly assume that consumers are uncertain about product quality q and thus their product valuation v. In our model, consumers know their match value with the product $v = \theta q$, but they are uncertain about q (which we interpret as popularity). The reason why consumers care about q when they already know v is because q affects the resale value of the product. Essentially, our modeling approach captures a unique characteristic of the art market, where consumers care about not only the consumption values of artworks, which are readily observable, but also the resale values of artworks. Our second modeling innovation is regarding the mechanism that supports the separating equilibrium. In existing literature, a separating equilibrium arises when a high price signals high quality due to differences in production costs (Wolinsky, 1983; Bagwell and Riordan, 1991) or repeated purchases (Milgrom and Roberts, 1986; Chen and Liu, 2022). In our model, these mechanisms have no bite; instead, the separating equilibrium exists because different art popularities lead to different demand elasticities. Additionally, some existing studies assume a segment of fully informed consumers (Bagwell and Riordan, 1991; Chen and Liu, 2022); in contrast, in our model, a segment of partially informed consumers emerge endogenously.

The paper proceeds as follows. Section 2 presents the model setup. Section 3 and 4 analyze the equilibrium and the effect of royalties on market outcomes under complete and incomplete information, respectively. Section 5 extends the main model in multiple directions. Section 6 concludes the paper.

2 Model Setup

We consider a game with an infinite time horizon. At time $t = 0$, an artist sells one artwork at price p_0. Buyers arrive over time, and each lives for one period before exiting the market. Specifically, buyer $t \in \{0, 1, \cdots\}$ arrives at time t and decides whether to buy the artwork or not.[5] If buyer t makes a purchase, she enjoys the artwork for one period and tries to resell it at price p_{t+1} to buyer $t+1$ at time $t+1$. If buyer t does not purchase the artwork, she exits the market by taking the outside option, the value of which is normalized to 0, and the game ends.[6] We assume that both the primary and resale markets are organized by take-it-or-leave-it offers.[7] Each time when the artwork is resold (for $t \geq 1$), the artist will collect a fixed percentage $r \in [0, 1]$ of the resale revenue as the royalty while the reseller keeps the remaining percentage of $1 - r$. ($r = 0$ represents the no-royalty case.) In the main model, we treat the royalty rate r as exogenously given and examine how it impacts the equilibrium outcome. In Section 5.1, we allow the artist to set the royalty rate, which can act as a signaling device for popularity alongside price.

Upon arrival, buyer t's expected utility from purchasing the artwork is,

$$u_t = v_t - p_t + \delta(1-r)\pi_{t+1}, \text{ for } t = 0, 1, \cdots, \tag{1}$$

where v_t is buyer t's match value with the artwork, π_{t+1} is the buyer's expected resale payoff at $t+1$, and $\delta \in (0, 1)$ is the time discounting factor that is assumed to be the same for both the artist and buyers. Equation (1) reflects that the infinite-horizon setup allows each buyer t to derive both consumption value (v_t)[8] and investment value through resales (π_{t+1}) from the artwork. We assume that v_t can be further decomposed as the following:

$$v_t = \theta_t q, \tag{2}$$

where θ_t captures the idiosyncratic part of the buyer's match value, and q captures the common value part shared by all buyers. θ_t is assumed to follow a uniform distribution on $[0, 1]$ and independent across t. The common value part q can be either q_H or q_L, where $q_H > q_L > 0$. Buyer 0 in the primary market does not observe q, i.e., the type of the artwork, and she has a

[5] Our assumption that only one buyer arrives in each period is without loss of generality. If there are multiple buyers arriving in a period, only the buyer with the highest willingness-to-pay has the opportunity to make a purchase, because there is only one unit of artwork supply in the market.

[6] We treat one period as the longest possible time that one is willing to hold and enjoy the art. If buyer t fails to resell the art in period $t+1$, she loses the opportunity to resell it anymore. In Section 5.3, we allow the buyer to continue enjoying the art with a positive salvage value if she fails to resell it. In Section 5.2, we consider another extension that allows for infinite resale opportunities for each buyer. Our main findings remain qualitatively unchanged in both extensions.

[7] Take-it-or-leave-it offers are the most common selling format for the primary market of both traditional art and NFT. Although auctions are often used for reselling traditional art, the auction market for NFT is still very limited. Our main result will be qualitatively the same if we instead assume that auctions are used for the resale markets, as long as the transaction probability does not always equal to one.

[8] The consumption value of an artwork may encompass aesthetic appreciation, emotional connection, and social/symbolic value that an artwork provides to its owner. These also apply to digital arts. For example, ownership of NFT artworks comes with high-resolution pictures. A pricing study of NFTs found that aesthetic attributes (e.g., higher colorfulness, texture complexity) significantly increase artwork price, indicating consumers derive value from the visual appeal of digital artworks (Alsultan et al., 2024).

prior belief that $q = q_H$ with probability $\lambda \in (0, 1)$, and $q = q_L$ with probability $1 - \lambda$.

While equation (2) looks identical to the classic utility specification with q interpreted as product quality and θ_t as buyer t's quality preference, the specification entails entirely different meanings in our setting because of the different information structure of the game. In particular, we assume that (1) buyer t observes v_t ($t \geq 0$); (2) buyer 0 does not observe θ_0 or q; (3) q is the artist's private information in the primary market ($t = 0$), and becomes common knowledge in resale markets ($t \geq 1$).[9] We justify these assumptions below by arguing that they capture the unique features of a typical art buying process.

In a classic product purchase setting (e.g. consumer electronics, food, movies, etc.), the product quality q and the product value v may not be observed by the buyer initially, but get revealed in the consumption process. In contrast, artwork buyers can examine almost all aspects of an artwork and knows how much they like it before making a purchase, and there is not much more to be revealed after purchase. Thus, it is reasonable to assume v_t is known to the buyer, as stated in Assumption (1). However, the buyer in the primary market does not know how much of her like or dislike is idiosyncratic to himself (θ_0) or commonly shared by other buyers (q), as in Assumption (2). By this understanding, q captures the market sentiment toward the artwork, and thus it is more appropriate to think of q as the *popularity* of the artwork among buyers. Assumption (3) captures the fact that the artist can have better access to aggregated information about the artwork than individual buyers and therefore is in an advantageous position to infer q in the primary market. In the resale markets, as buyers observe more information, especially the purchase history of the artwork, q gets revealed to buyers as well. As we show below, the second part of assumption (3) is self-fulfilling in the sense that only the separating equilibrium exists in equilibrium, so buyers in the resale markets can indeed rationally infer the type of artwork.

In a classic purchase setting, buyers care about q because it affects the product value v. One may wonder why in the art market setting, buyer t still cares about q given that she already knows v_t. This is because the value of q, capturing the market sentiment towards the artwork, determines her expected payoff from reselling the artwork. Another subtle point is that θ_t in our model is not only buyer-specific but also product-specific (it has no product subscript because we only model a single artwork). In other words, a higher θ_t means that buyer t prefers this specific artwork, but not necessarily has higher valuations for other artworks. In contrast, θ is usually interpreted as quality preference and is buyer-specific in classic models.

In terms of the equilibrium concept, we consider pure-strategy Perfect Bayesian Equilibria (PBE). In the primary market with $t = 0$, the artist's price serves as a signal for the type of artwork. Based on the prior belief, price, and her match value, buyer 0 updates her belief using Bayes' rule whenever plausible. In equilibrium, the artist decides the price to maximize the expected profit according to the buyer's posterior belief and best responses. To guarantee the equilibrium uniqueness, we adopt the *intuitive criterion* to rule out equilibria that rely on unreasonable off-equilibrium-path beliefs.

[9] In Section 5.4, we consider an extension where the artwork's popularity in resale marekts is never revealed but is endogenously determined by the primary buyer's opinion. In Section 5.5, we examine another extension where popularity fluctuates stochastically in resale markets.

3 Complete Information Market

Before analyzing the market with incomplete information as described above, we first consider the complete information case, where the popularity of artwork q is public information for all buyers, including in the primary market.

We solve the game by backward induction. First, let's consider the resale market at time $t \geq 1$. Buyer $t-1$ sets the price at p_{jt} to maximize her expected resale payoff $(1-r)\pi_{jt}$, where $j \in \{H, L\}$ denotes the artwork's popularity type. Buyer t will purchase if and only if $u_{jt} = \theta_t q_j - p_{jt} + \delta(1-r)\pi_{j,t+1} \geq 0$, which implies that the probability of buyer t making a purchase of the type-j artwork at price p_{jt} (i.e., the transaction probability) is

$$d_{jt}(p_{jt}) = \Pr\left(\theta_t \geq \frac{p_{jt} - \delta(1-r)\pi_{j,t+1}}{q_j}\right) = 1 - \frac{p_{jt} - \delta(1-r)\pi_{j,t+1}}{q_j}.$$

Therefore, the optimal price should be $p^*_{jt} = \arg\max_{p_{jt}}(1-r)\pi_{jt} = \frac{1}{2}\left(q_j + \delta(1-r)\pi_{j,t+1}\right)$, and correspondingly, buyer $t-1$'s expected resale payoff under the optimal price is,

$$\pi^*_{jt} \equiv p^*_{jt} d_{jt}(p^*_{jt}) = \frac{\left(q_j + \delta(1-r)\pi_{j,t+1}\right)^2}{4q_j}. \tag{3}$$

Notice that the resale markets are time-stationary, so we have $\pi_{j,t+1} = \pi^*_{jt} \equiv \pi^*_j$ in equilibrium. This observation enables us to use equation (3) to solve for π^*_j, together with the equilibrium resale price p^*_j and per-period transaction probability $d^*_j \equiv d_{jt}(p^*_j)$. We have dropped the time subscript because all resale market outcomes are identical in equilibrium.

Next, we consider the primary market, where the artist sets price $p_{j0} \equiv P_j$ to maximize her expected profit, taking into account both the instantaneous sales revenue and future royalty payments:

$$\Pi^*_j = \max_{P_j}\left(P_j + \underbrace{\delta r \sum_{t=0}^{\infty}(\delta d^*_j)^t \pi^*_j}_{\text{royalties}}\right)\Pr\left(u_{0j} \geq 0\right) = \max_{P_j}\left(P_j + \frac{r\delta\pi^*_j}{1-\delta d^*_j}\right)\left(1 - \frac{P_j - \delta(1-r)\pi^*_j}{q_j}\right).$$

This optimization problem can be easily solved given its quadratic form, and we have the following proposition summarizing the market outcome under complete information. Proofs to all formal statements in this paper are provided in Appendix without further mentioning.

Proposition 1 (Complete Information). *Under complete information, for an artwork of type $j \in \{H, L\}$:*

(i) In each resale market ($t \geq 1$), the equilibrium price is $p^*_j = \frac{q_j}{1+\sqrt{1-\delta(1-r)}}$, the transaction probability is $d^*_j = \frac{1}{1+\sqrt{1-\delta(1-r)}}$, and the expected resale profit (before royalty) is $\pi^*_j = \frac{q_j}{[1+\sqrt{1-\delta(1-r)}]^2}$;

(ii) In the primary market ($t = 0$), the equilibrium price is $P^*_j = \frac{(1-\alpha(\delta,r))q_j}{1+\sqrt{1-\delta(1-r)}}$, the transaction probability is $D^*_j \equiv \Pr\left(u_{0j} \geq 0\right) = \frac{(1+\alpha(\delta,r))}{1+\sqrt{1-\delta(1-r)}}$, and the artist's expected profit is $\Pi^*_j = \frac{(1+\alpha(\delta,r))^2 q_j}{[1+\sqrt{1-\delta(1-r)}]^2}$, where $\alpha(\delta, r) \equiv \frac{r[1-\sqrt{1-\delta(1-r)}]}{2[\sqrt{1-\delta(1-r)}-r]} \geq 0$;

(iii) A higher royalty rate lowers the equilibrium price, transaction probability, as well as the artist's and resellers' expected profit in both the primary and resale markets. It also lowers the total social welfare.

In resale markets, royalties act as a tax for resellers, so it will reduce buyers' willingness-to-pay, because buyers are future resellers. This leads to a decrease in the resale price as well as the transaction probability in each resale market. Consequently, resellers' expected profit also gets lower. More interestingly, the artist's expected profit and the transaction probability in the primary market also decrease with the royalty rate. Although a higher royalty rate allows the artist to collect higher payments from future resales, its negative effect on buyers' willingness-to-pay is so strong that it dominates the positive effect of increased royalty payments, and consequently, the artist always gets hurt with a higher royalty under complete information. Lastly, royalties create social inefficiency because it reduces transaction probability in both primary and resale markets.

4 Incomplete Information Market

In this section, we study the incomplete information market, where the artwork popularity is the artist's private information in the primary market. To build our understanding progressively, we analyze the equilibrium without royalties ($r = 0$) first, which illuminates why a high price can signal high popularity.

4.1 Incomplete Information without Royalties

The equilibrium outcome for the resale markets is the same as under complete information characterized by Proposition 1(i). In the primary market, buyer 0 observes her match value $v_{j0} = \theta_0 q_j$, which serves as a noisy signal of the artwork popularity q_j. Specifically, given $\theta_0 \in [0, 1]$, we have $v_{L0} \leq q_L$, and hence buyer 0 can perfectly infer that $q_j = q_H$ if she observes $v_{j0} > q_L$. On the other hand, if she observes $v_{j0} \leq q_L$, the buyer remains uncertain about the artwork's popularity, and she resorts to the price signal to make a distinction in a separating equilibrium and applies Bayesian updating on her belief in a pooling equilibrium.

Now we consider the artist's pricing decision. Let $\Pi_j(P; \mu)$ denote the j-type artist's profit when she sets the price at P and the buyer 0's belief about the artist being high-type is μ. The following lemma shows that pooling equilibria do not exist.

Lemma 1. *Under incomplete information without royalties, there does not exist a pooling equilibrium that survives the intuitive criterion.*

We prove Lemma 1 in Appendix by showing that for any possible pooling equilibrium with price $\widetilde{P}$, there exists $P' > \widetilde{P}$ such that the low-type artist has no incentive to charge P' under any belief as $\Pi_L(P'; 1) < \Pi_L(\widetilde{P}; \lambda)$, while the high-type artist strictly benefits from deviating to P' as $\Pi_H(P'; 1) > \Pi_H(\widetilde{P}; \lambda)$. The reason why the high-type artist can signal herself out by charging a high price of P' is that buyer 0's match value $v_{j0} = \theta_0 q_j$ serves as a noisy signal of the artwork popularity q_j, so the buyer is more optimistic about the resale value of the artwork produced by a high-type artist. In plain words, if the buyer likes an artwork more, she will be more likely to believe that others also like the artwork, and thus she expects a higher resale value. Consequently, the high-type artist will fare better than the low-type one with a high price.

Lemma 1 implies that we only need to focus on the separating equilibrium. There are two cases to study. Denote P_j^* as j-type artist's optimal price under complete information. When $\Pi_L(P_L^*; 0) \geq \Pi_L(P_H^*; 1)$, the low-type artist does not benefit from mimicking the high-type artist by charging the high-type optimal price. Thus, the low-type artist will still set the price at the optimal level P_L^* as if under complete information, and the high-type has no incentive to deviate from the optimal price P_H^* either. Then both types will set the optimal price as if under complete information in equilibrium—we call this case the *Costless Separating equilibrium*. When $\Pi_L(P_L^*; 0) < \Pi_L(P_H^*; 1)$, the low-type will benefit from mimicking the high-type by charging P_H^*. To prevent the low-type from mimicking, the high-type artist has to raise the price from P_H^* to a higher level $\widehat{P}_H$. The intuitive criterion can further help us pin down $\widehat{P}_H$: it is the price level that makes the low-type indifferent between mimicking or not, i.e., $\Pi_L(P_L^*; 0) = \Pi_L(\widehat{P}_H; 1)$. We call this the *Costly Separating equilibrium*. Proposition 2 formally characterizes these two types of equilibrium under different conditions and proves their uniqueness.

Proposition 2 (Incomplete Information without Royalties)**.** *Suppose the artwork's popularity is the artist's private information in the primary market, and there is no royalty ($r = 0$).*

(i) In the resale markets, the equilibrium is the same as under complete information.

(ii) In the primary market, the unique equilibrium that survives the intuitive criterion is the following separating equilibrium:

*(a) (**Costless Separating**) if $q_H/q_L \geq 1/\sqrt{1-\delta}$, the artist charges the same price as under complete information, $P_j^*\big|_{r=0} = \frac{q_j}{1+\sqrt{1-\delta}}$ for $j \in \{H, L\}$;*

*(b) (**Costly Separating**) if $q_H/q_L < 1/\sqrt{1-\delta}$, the high-type artist charges a higher price than under complete information, $\widehat{P}_H^0 > P_H^*\big|_{r=0}$, and the low-type artist charges the same price as under complete information, $P_L^*\big|_{r=0} = \frac{q_L}{1+\sqrt{1-\delta}}$.*

The off-equilibrium-path belief can be specified as $\mu(P') = 0$ for any off-equilibrium-path price P'.

The closed-form expression of $\widehat{P}_H^0$ is relegated to Appendix. Proposition 2 shows that a high price can signal high popularity of the artwork. The key driving force is that the low-type artist suffers a greater demand loss from a high price than the high-type. To be more specific, the low-type artist can mimic the high-type's price to make buyer 0 believe that the artwork is of high-type, so that the buyer will make a purchase if $\theta_0 q_L + \delta\pi_H^* - P_H \geq 0$. This implies that when the low-type artist mimics the high-type artist, she faces the following trade-off: on one hand, buyer 0 will have a higher willingness-to-pay because she expects the resale value to be π_H^* instead of π_L^*; on the other hand, the low-type artist suffers a demand loss by charging a price higher than the optimal level P_L^*. We can easily observe that the low-type's transaction probability $1 - (P_H - \delta\pi_H^*)/q_L$ decreases in P_H at a faster rate than the high-type's transaction probability $1 - (P_H - \delta\pi_H^*)/q_H$. Thus, the high-type artist can prevent the low-type from mimicking by setting a sufficiently high price.

When the difference between q_H and q_L is sufficiently large ($q_H/q_L \geq 1/\sqrt{1-\delta}$), the low-type artist would not mimic the high-type's strategy because the demand loss from charging P_H cannot be compensated by the gain from buyer 0's higher willingness-to-pay. In this case, the high-type can adopt the optimal price under complete information and still signal her high popularity, which constitutes the Costless Separating equilibrium. When the difference between q_H and q_L is small ($q_H/q_L < 1/\sqrt{1-\delta}$), the high-type artist needs to costly distort her price to signal high popularity, so we call it the Costly Separating equilibrium.

4.2 Incomplete Information with Royalties

Now we are ready to examine the general case with royalties ($r \geq 0$). Similarly, we can show that there exists no pooling equilibrium, and the following proposition characterizes the unique separating equilibrium, which follows the same structure as that in Proposition 2.

Proposition 3 (Incomplete Information with Royalties)**.** *Suppose the artwork's popularity is the artist's private information in the primary market, and the royalty rate is r.*

(i) In the resale markets, the equilibrium is the same as in the complete information case with royalty rate r.

(ii) In the primary market, the unique equilibrium that survives the intuitive criterion is the following separating equilibrium:

*(a) (**Costless Separating**) if $q_H/q_L \geq k(\delta, r)$, the artist charges the same price as under complete information $P_j^* = \frac{[1-\alpha(\delta,r)]q_j}{1+\sqrt{1-\delta(1-r)}}$ for $j \in \{H, L\}$;*

*(b) (**Costly Separating**) if $q_H/q_L < k(\delta, r)$, the high-type artist charges a higher price than under complete information, $\widehat{P}_H > P_H^*$, and the low-type artist charges the same price as under complete information $P_L^* = \frac{[1-\alpha(\delta,r)]q_L}{1+\sqrt{1-\delta(1-r)}}$.*

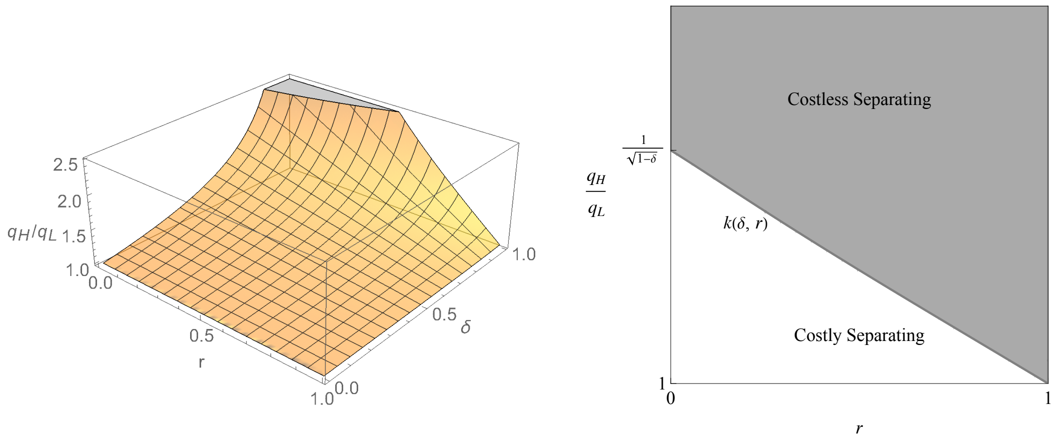
The off-equilibrium-path belief can be specified as $\mu(P') = 0$ for all off-equilibrium-path price P'.

(iii) $k(\delta, r)$ increases with δ and decreases with r, implying that the Costless Separating equilibrium is more likely to hold when the artist and buyers are more myopic, or the royalty rate is higher.

The closed-form expressions of $k(\delta, r)$ and $\widehat{P}_H$ are provided in Appendix. Proposition 3 implies that while the existence of royalties does not change the general structure of the equilibrium, it does have an impact on two things: (1) the threshold $k(\delta, r)$ that delimits the Costless Separating and Costly Separating equilibria, and (2) the equilibrium prices P_H^*, $\widehat{P}_H$ and P_L^*.

Similar to the case without royalties, when q_H/q_L is higher, the Costless Separating equilibrium is more likely to hold, which is very intuitive. The difference is that the boundary between the Costless Separating and Costly Separating equilibria now depends on not only δ but also r. Figure 1(a) illustrates the boundary between the two types of equilibria in relation to the royalty rate r and the discount rate δ. The curved surface represents $k(\delta, r)$. The space below the surface represents the Costly Separating equilibrium, and the space above the surface represents the Costless Separating equilibrium. Figure 1(b) shows it in a two-dimensional plane with δ fixed.

Figure 1: Parameter Space for the Costly & Costless Separating Equilibrium



(a) (b)

Proposition 3(iii) and Figure 1 reveal that a higher royalty r makes the Costless Separating equilibrium easier to sustain. This is because a higher r reduces the low-type artist's incentive to mimic, for the following two reasons. First, the difference between the high-type's and low-type's resale values, $(1-r)(\pi_H^* - \pi_L^*)$, decreases with the royalty rate r, meaning that the benefit of mimicking decreases with r. Second, when the royalty rate r increases, the low-type artist cares more about the transaction probability in the primary market because she will be able to collect a larger fraction of royalties from future transactions, which hinges upon the artwork being sold in the primary market. As a result, it becomes more costly for the low-type artist to charge a high price to mimic, as it lowers the transaction probability in the primary market.

Proposition 3(iii) and Figure 1 also reveal that when the discount rate δ is smaller, the Costless Separating equilibrium is more likely to sustain. This is because when δ is smaller, buyer 0 cares less about the future resale value, which reduces the low-type artist's incentive to mimic. Although a lower δ also makes the artist care less about the royalties, its impact on buyer 0's willingness-to-pay plays a dominant role. Thus, a lower δ makes the Costless Separating equilibrium more likely to hold.

From Figure 1(b), we can clearly observe that when $q_H/q_L < 1/\sqrt{1-\delta}$, a threshold $\widehat{r}$ exists to distinguish between the two types of separating equilibria, as stated below. The proof is straightforward given Proposition 3 and thus omitted.

Corollary 1. *Under incomplete information with the artwork's popularity being the artist's private information:*

(i) If $q_H/q_L \geq 1/\sqrt{1-\delta}$, the unique equilibrium is the Costless Separating equilibrium for all $0 \leq r \leq 1$;

(ii) If $q_H/q_L < 1/\sqrt{1-\delta}$, there exists a threshold $\widehat{r}$ such that the unique equilibrium is the Costly Separating equilibrium when $0 \leq r < \widehat{r}$ and the Costless Separating equilibrium when $\widehat{r} \leq r \leq 1$.

An interesting special case is when the discount factor δ approaches zero, only the Costless Separating equilibrium can sustain. This is because when δ is zero, buyer 0 only cares about the present payoff and ignores the resale value in the future, which eliminates uncertainty in the primary market, and the model degenerates to the complete information case.

Another special case is that when r approaches 1, we have $\lim_{r\to 1} k(\delta, r) = 1 < q_H/q_L$ and only the Costless Separating equilibrium holds. The intuition is that when $r \to 1$, buyer 0 no longer cares about the resale value of the artwork given it is fully extracted by the artist, and therefore, the low-type artist no longer has any incentive to mimic the high-type.

Next, based on the equilibrium characterization by Proposition 3, we investigate the effect of royalties on equilibrium prices, profits as well as social welfare.

Effect of Royalties on Prices and the Price Distortion

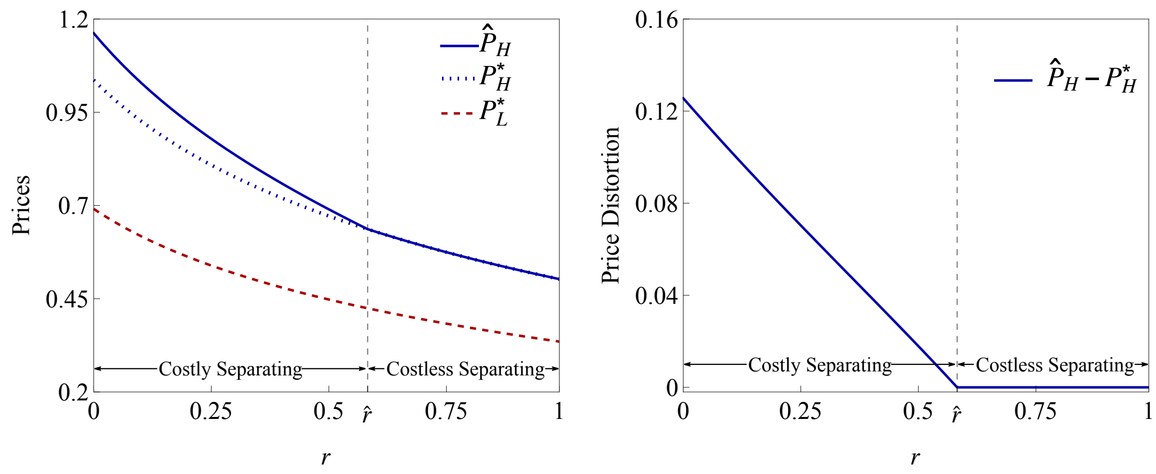
We define the high-type artist's price distortion as the difference between her equilibrium prices under incomplete and complete information, $\widehat{P}_H - P_H^*$. The following proposition characterizes the effect of royalties on equilibrium prices and price distortion in the primary market.

Proposition 4 (Effect of Royalty Rate on Equilibrium Prices and Price Distortion)**.** *Under incomplete information with the artwork's popularity being the artist's private information:*

(i) The equilibrium prices in the primary market for both types of artworks decrease with r.

(ii) If $q_H/q_L < 1/\sqrt{1-\delta}$, the high-type artist's price distortion, $\widehat{P}_H - P_H^*$ decreases with r for $r \in [0, \widehat{r}]$ and stays at 0 for $r \in [\widehat{r}, 1]$; if $q_H/q_L \geq 1/\sqrt{1-\delta}$, the Costless Separating equilibrium holds, so there is no price distortion. The low-type artist never has price distortion.

Figure 2: Effect of Royalty Rate on Prices and Price Distortion in Equilibrium



(a) Prices (b) Price Distortion (High-Type)

Note. $\delta = 0.8, q_H = 1.5, q_L = 1$ in this illustration.

Figure 2(a) shows the equilibrium prices of both types of artworks in the primary market under incomplete information (the solid line) and complete information (the dashed lines).

Consistent with Proposition 1 and Proposition 4, the figure shows that all equilibrium prices decrease with royalty rate r. Consistent with Proposition 2 and Proposition 3, in the Costly Separating equilibrium region, the equilibrium price under incomplete information (the solid line) is higher than that under complete information (the dashed line), i.e., $\widehat{P}_H > P_H^*$. The high-type artist's price distortion, as represented by the difference between these two lines, narrows as r increases and becomes zero at $r = \widehat{r}$. The price distortion is also separately plotted in Figure 2(b). The intuition is similar to that of Proposition 3: as the royalty rate r increases, the low-type artist benefits less from mimicking, making it easier for the high-type artist to separate from the low-type artist. Thus, the high-type artist can distort less from the efficient price level and still achieve separation.

Effect of Royalties on Artist Profit

Proposition 5 presents the impact of the royalty rate on the artist's profit, which encompasses the sales profit from the primary market and the expected discounted royalties obtained from all future resales.

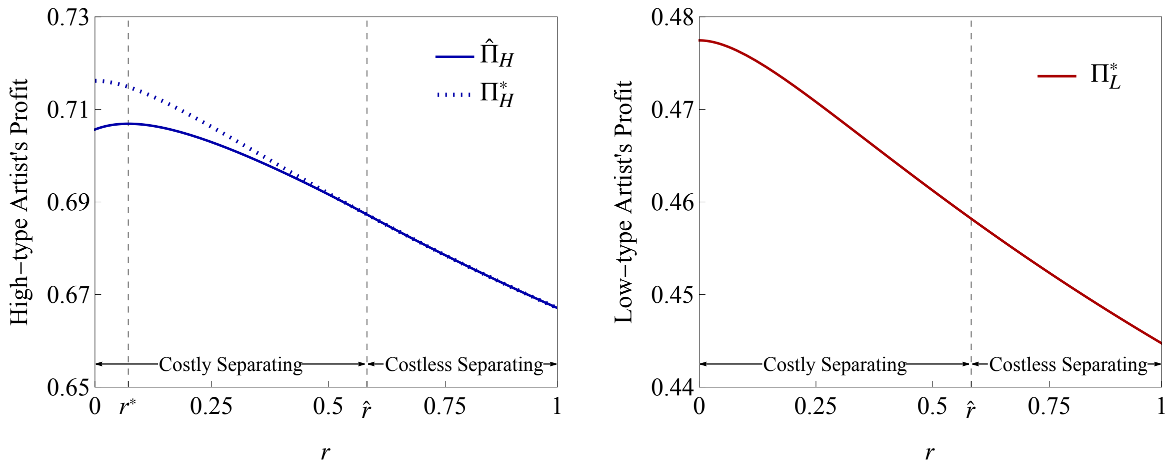
Proposition 5 (Effect of Royalty Rate on Artist Profit)**.** *Under incomplete information with the artwork's popularity being the artist's private information:*

(i) When $q_H/q_L < 1/\sqrt{1-\delta}$ and $0 \leq r < \widehat{r}$, the high-type artist's profit is lower than that under complete information, and it first increases and then decreases in r, with a unique $r^* \in (0, \widehat{r})$ that maximizes the profit;

(ii) Otherwise, the high-type artist's profit is the same as that under complete information and decreases with r.

(iii) The low-type artist's profit is the same as that under complete information and decreases with r.

Figure 3: Effect of Royalty Rate on Artist's Profit



(a) High-Type (b) Low-Type

Note. $\delta = 0.8, q_H = 1.5, q_L = 1$ in this illustration.

Figure 3 illustrates Proposition 5. Compared to the complete information benchmark, where both types of artists' profits always decrease with r, the new and distinct finding under incomplete information is that in the Costly Separating equilibrium, the high-type artist's profit (the solid line in Figure 3(a)) is non-monotonic with respect to r. This is because a higher royalty rate has two effects on the high-type artist's profit. On one hand, it reduces the low-type artist's incentive to mimic, and thus allows the high-type artist to separate at a lower price that is closer to the optimal level, which benefits the high-type artist. On the other hand, it reduces the resale value of the artwork, and thus buyer 0 will have a lower willingness-to-pay, which hurts the high-type artist's profit. These two effects together make the high-type artist's profit first increase and then decrease in r in the Costly Separating equilibrium region, and we further prove that there exists a unique $r^* \in (0, \widehat{r})$ that maximizes the high-type artist's profit.

In summary, royalties always hurt the low-type artist under both complete and incomplete information; they also hurt the high-type artist under complete information. However, a relatively low level of royalty rate can benefit the high-type artist because it alleviates his burden to costly signal his popularity.

Effect of Royalties on Social Welfare

Lastly, we explore the impact of royalties on social welfare, which is the sum of consumer surplus and the artist's profit. Since the payment between the seller (artist) and buyer in each time period is just a transfer of wealth, we can calculate the social welfare by summing up the consumption utility $\theta_t q_j$ over buyer t who purchases the artwork. We calculate the social welfare for the high-type and low-type artwork separately. Proposition 6 characterizes the effect of royalty rate on social welfare.

Proposition 6 (Effect of Royalty Rate on Social Welfare)**.** *Under incomplete information with the artwork's popularity being the artist's private information:*

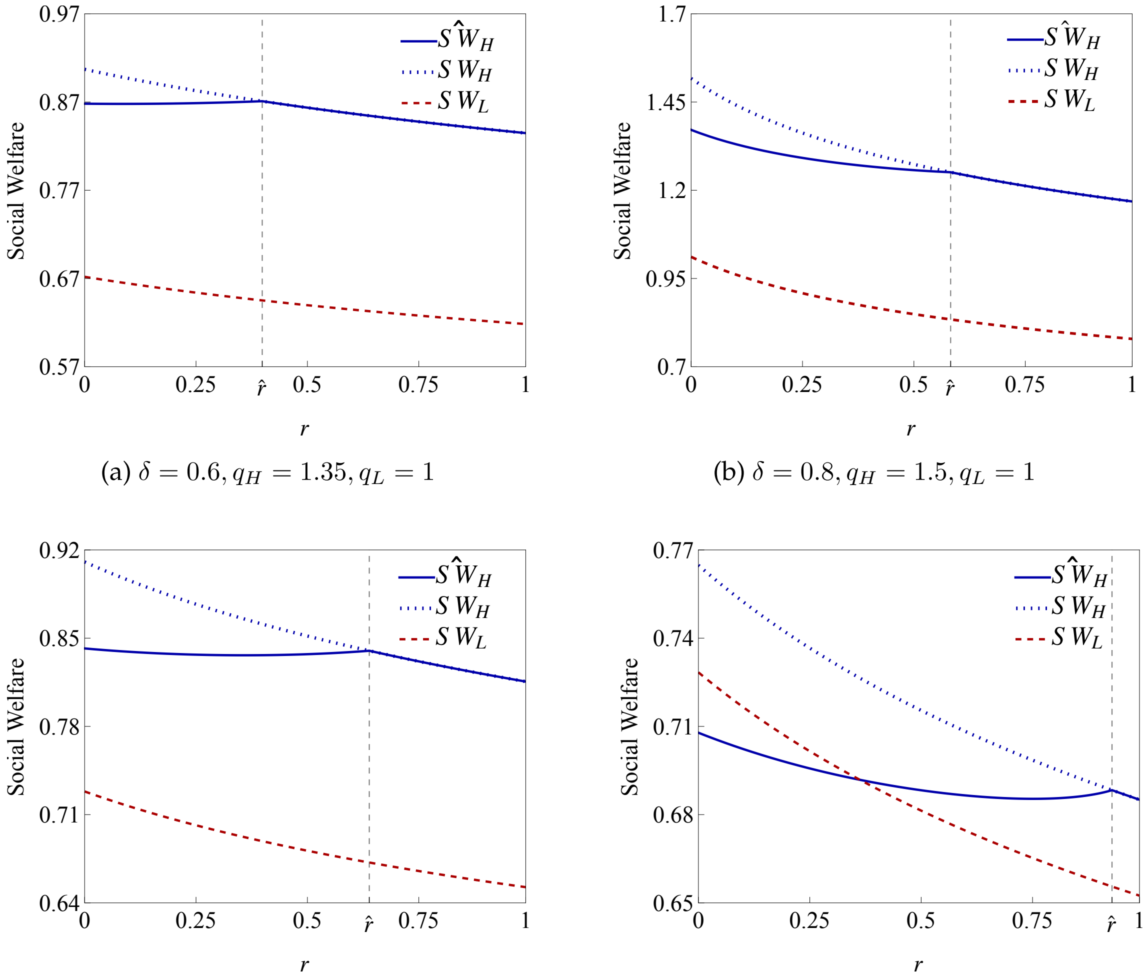
(i) If $q_H/q_L < 1/\sqrt{1-\delta}$ and $0 \le r < \widehat{r}$ (i.e., in the Costly Separating equilibrium region), the social welfare for the high-type artwork may increase, decrease or be non-monotonic with r;

(ii) Otherwise, the social welfare for the high-type artwork is the same as that under complete information and decreases with r.

(iii) The social welfare for the low-type artwork is the same as that under complete information and decreases with r.

Figure 4 illustrates how the social welfare changes with r under various parameter settings. As stated in Proposition 6, the social welfare for the low-type artwork and that for the high-type artwork under the Costless Separating equilibrium decrease with r. This is intuitive because the low-type artist and the high-type artist under the Costless Separating equilibrium behave as if under complete information, and royalties always reduce the transaction probabilities in both the primary and resale markets under complete information. The more interesting result is that, in the Costly Separating equilibrium region ($r \in [0, \widehat{r}]$), the social welfare for the high-type artwork $\widehat{SW}_H$ changes with r in various patterns: $\widehat{SW}_H$ can increase with r (Figure 4(a)), decrease with r (Figure 4(b)), or first decrease and then increase with r (Figure 4(c) and (d)). Moreover, Figure 4(d) shows that when q_H and q_L are relatively close, the welfare loss from the price distortion on the high-type artwork could be so strong that $\widehat{SW}_H$ can be even lower than SW_L.

Figure 4: Effect of Royalty Rate on Social Welfare



(a) $\delta = 0.6, q_H = 1.35, q_L = 1$

(b) $\delta = 0.8, q_H = 1.5, q_L = 1$

(c) $\delta = 0.65, q_H = 1.25, q_L = 1$

(d) $\delta = 0.65, q_H = 1.05, q_L = 1$

Now we explain why the social welfare for the high-type artwork can have these different patterns. Under the Costly Separating equilibrium, the transaction probability for the high-type artwork is $\widehat{D}_H \equiv \Pr(\theta_0 \geq [\widehat{P}_H - \delta(1-r)\pi^*_H]/q_H)$ in the primary market, and is $d^*_H = \Pr(\theta_t \geq [p^*_H - \delta(1-r)\pi^*_H]/q_H)$ in each resale market. Therefore, we have

$$\begin{aligned}\widehat{SW}_H &= \int_{1-\widehat{D}_H}^{1} \theta_0 q_H d\theta_0 + \delta \widehat{D}_H \sum_{t=0}^{\infty} (\delta d^*_H)^t \int_{1-d^*_H}^{1} \theta_t q_j d\theta_t \\ &= \frac{q_H}{2}(1-(1-\widehat{D}_H)^2) + \frac{\delta \widehat{D}_H}{1-\delta d^*_H}\frac{q_H}{2}(1-(1-d^*_H)^2),\end{aligned}$$

where the first term represents the social welfare from the primary market and the second term is the social welfare from the resale markets. To examine how $\widehat{SW}_H$ changes with r, we decompose the effect of r on $\widehat{SW}_H$ into two parts:

$$\frac{d\widehat{SW}_H}{dr} = \left[q_H(1-\widehat{D}_H) + \frac{\delta(1-(1-d_H^*)^2)q_H}{2(1-\delta d_H^*)}\right]\frac{d\widehat{D}_H}{dr} + \frac{[2\delta(1-d_H^*)+(\delta d_H^*)^2]\widehat{D}_H q_H}{2(1-\delta d_H^*)^2}\frac{dd_H^*}{dr},$$

where the first part captures the impact of r through affecting the transaction probability in the primary market $\widehat{D}_H$ and the second term captures the effect of r through the transaction probability in each resale market d_H^*. From Proposition 1, we know the second term is negative, since royalties act as a form of taxation that creates deadweight loss and necessarily reduces the transaction probability in complete-information resale markets. As we have shown in Proposition 4, in the Costly Separating equilibrium region, a higher royalty rate r reduces the price distortion for the high-type artist in the primary market, which can lead to a higher primary-market transaction probability $\widehat{D}_H$, and thus a higher social welfare. Combining the two effects together, the total social welfare for the high-type artwork may increase, decrease, or be non-monotonic with r.

5 Extensions

We extend the main model along multiple directions. The proofs to all formal statements in this section are relegated to the Online Appendix.

5.1 Artist's Endogenous Decision on Royalty Rate

In the main model, we assume exogenous royalty rate r and focus on how r impacts the equilibrium outcome. In this extension, we examine what happens if r is endogenously decided by the artist. In particular, we assume that at $t = 0$, the artist chooses the royalty rate r and price P, which can jointly signal the artwork's popularity type $j \in \{H, L\}$. The other assumptions are the same as in the main model.

We first consider the case of complete information. The artist simply chooses the price and royalty rate that maximize its expected profit. By Proposition 1, the artist's profit decreases with r, yielding the optimal royalty rate $r_j^* = 0$ and optimal price $P_j^* = q_j/(1+\sqrt{1-\delta})$ for $j \in \{H, L\}$.

Next, we consider the incomplete information case. Proposition 7 characterizes the equilibrium, where subscript r is used to signify the case of endogenous royalty rate.

Proposition 7 (Royalty Rate Chosen by the Artist, Incomplete Information)**.** *Suppose the artwork's popularity is the artist's private information in the primary market, and the artist chooses the royalty rate r. In the primary market, the unique equilibrium that survives the intuitive criterion is the following separating equilibrium:*

(a) (***Costless Separating***) *if $q_H/q_L \geq 1/\sqrt{1-\delta}$, the artist chooses the same strategy as under complete information: $r_j^* = 0$ and $P_j^* = q_j/(1+\sqrt{1-\delta})$ for $j \in \{H, L\}$;*

(b) (***Costly Separating***) *if $q_H/q_L < 1/\sqrt{1-\delta}$, the high-type artist chooses royalty rate $\widehat{r}_H^* > 0$ and $\widehat{P}_{Hr} > P_H^*$ (the subscript r represents the case where the royalty rate r is endogenously cho-*

sen by the artist), and the low-type artist chooses the same price and royalty rate under complete information, $r_L^* = 0$ *and* $P_L^* = q_L/(1+\sqrt{1-\delta})$.

The off-equilibrium-path belief can be specified as $\mu(P', r') = 0$ *for any off-equilibrium-path strategy* (P', r').

We can see that the findings from our main model are fully robust under endogenous royalty rate. In the Costly Separating equilibrium, the high-type artist combines a positive royalty rate with an upward price distortion to signal its high popularity, because a positive royalty rate reduces the amount of price distortion needed to achieve separation and thus increases the artist's expected profit.

5.2 Infinite Resale Opportunities

In the main model, we assume that the seller (previous buyer) in each time period t only has one opportunity to sell the artwork before exiting the market. In this extension, we allow infinite resale opportunities so that if the seller at resale market t ($t \geq 1$) fails to sell the artwork to buyer t, she can attempt to sell it to the next buyer $t+1$ in time period $t+1$, and this resale process never ends until the seller succeeds. Let's first characterize the equilibrium under complete information, where subscript I signifies the case with infinite resale opportunities.

Proposition 8 (Infinite Resale Opportunities, Complete Information)**.** *Suppose the artwork's popularity is common knowledge, and there are infinite resale opportunities for each buyer in resale markets.*

(i) In each resale market ($t \geq 1$)*, the equilibrium price is* $p_{jI}^* = \frac{[1+\sqrt{(1-\delta)[1-(1-r)\delta]}]q_j}{[\sqrt{1-(1-r)\delta}+\sqrt{1-\delta}]^2}$*, the transaction probability is* $d_{jI}^* = \frac{\sqrt{1-\delta}}{[\sqrt{1-\delta}+\sqrt{1-(1-r)\delta}]}$*, and the expected resale profit (before royalty) is* $\pi_{jI}^* = \frac{q_j}{[\sqrt{1-(1-r)\delta}+\sqrt{1-\delta}]^2}$.

(ii) In the primary market ($t = 0$)*,*

- *Case (a): if* $0 < \delta < 4/5$*, or* $4/5 \leq \delta < 2(\sqrt{2}-1)$ *and* $\frac{\sqrt{5\delta-4}(3\delta-2+\sqrt{\delta(5\delta-4)})}{2\sqrt{\delta}(1-\delta)} < r < 1$*, the equilibrium price is* $P_{jIa}^* = \frac{(1-R_I)q_j+\delta(1-r)\pi_{jI}^*}{2}$*, the transaction probability is* $D_{jIa}^* = \frac{(1+R_I)q_j+\delta(1-r)\pi_{jI}^*}{2q_j}$*, and the artist's expected profit is* $\Pi_{jIa}^* = \frac{\left((1+R_I)q_j+\delta(1-r)\pi_{jI}^*\right)^2}{4q_j}$*, where* $R_I = \frac{r\delta(1+\sqrt{(1-\delta)[1-(1-r)\delta]})}{\sqrt{1-\delta}[\sqrt{1-\delta}+\sqrt{1-(1-r)\delta}]^3}$*; (the subscript "a" represents this case (a), and similarly for case (b))*
- *Case (b): if* $4/5 \leq \delta < 2(\sqrt{2}-1)$ *and* $0 \leq r \leq \frac{\sqrt{5\delta-4}(3\delta-2+\sqrt{\delta(5\delta-4)})}{2\sqrt{\delta}(1-\delta)}$*, or if* $2(\sqrt{2}-1) \leq \delta < 1$*, the equilibrium price is* $P_{jIb}^* = \delta(1-r)\pi_{jI}^*$*, the transaction probability is* $D_{jIb}^* = 1$*, and the artist's expected profit is* $\Pi_{jIb}^* = \delta(1-r)\pi_{jI}^* + R_I q_j$.

(iii) A higher royalty rate lowers the equilibrium price, transaction probability, as well as the artist's and resellers' expected profit in both the primary and resale markets.

Compared to the main model, a key distinction of this extension is that in case (b), the expected royalties from future resales are so substantial that the artist finds it optimal to set a low enough price so that buyer 0 will be willing to purchase it for sure: this price equals the expected resale value $\delta(1-r)\pi^*_{jI}$, so buyer 0 will be willing to purchase the artwork even when her own valuation of the artwork is zero. Despite this distinction, in this extension, a higher royalty rate still lowers the equilibrium price and everyone's expected profit under complete information, for a similar intuition. Next, we consider the case with incomplete information.

Proposition 9 (Infinite Resale Opportunities, Incomplete Information)**.** *Suppose the artwork's popularity is the artist's private information in the primary market, and there are infinite resale opportunities for each buyer in resale markets. In the primary market, the unique equilibrium that survives the intuitive criterion is the following separating equilibrium:*

- *Case (a): When $0 < \delta < 4/5$, or when $4/5 \le \delta < 2(\sqrt{2}-1)$ and $\frac{\sqrt{5\delta-4}(3\delta-2+\sqrt{\delta(5\delta-4)})}{2\sqrt{\delta}(1-\delta)} < r < 1$,*
  - *(**Costless Separating**) if $q_H/q_L \ge k_I(\delta, r)$, the artist charges the same price under complete information $P^*_{jIa} = \frac{(1-R_I)q_j+\delta(1-r)\pi^*_{jI}}{2}$ for $j \in \{H, L\}$;*
  - *(**Costly Separating**) if $q_H/q_L < k_I(\delta, r)$, the high-type artist charges a higher price than under complete information, $\widehat{P}_{HIa} > P^*_{HIa}$, and the low-type artist charges the same price as under complete information $P^*_{LIa} = \frac{(1-R_I)q_L+\delta(1-r)\pi^*_{LI}}{2}$.*
- *Case (b): When $4/5 \le \delta < 2(\sqrt{2}-1)$ and $0 \le r \le \frac{\sqrt{5\delta-4}(3\delta-2+\sqrt{\delta(5\delta-4)})}{2\sqrt{\delta}(1-\delta)}$, or $2(\sqrt{2}-1) \le \delta < 1$, only **Costly Separating** equilibrium exists: the high-type artist charges a higher price than under complete information, $\widehat{P}_{HIb} > P^*_{HIb}$, and the low-type artist charges the same price as under complete information $P^*_{LIb} = \delta(1-r)\pi^*_{LI}$.*

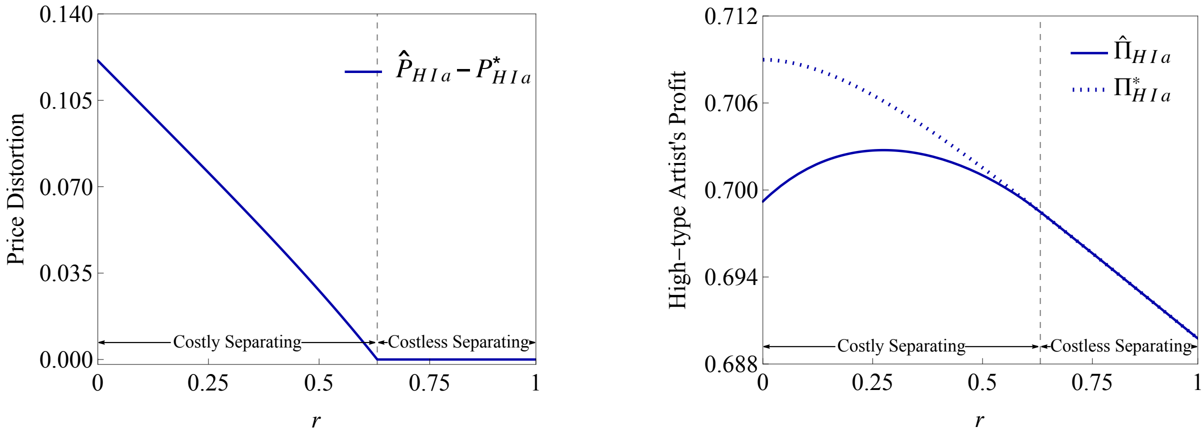
The off-equilibrium-path belief can be specified as $\mu(P') = 0$ for all off-equilibrium-path price P'. Moreover, in the Costly Separating equilibrium in both cases (a) and (b), there exists an non-empty interval of r, in which the high-type artist's price distortion decreases with r, and the high-type artist's profit increases with r.

The key difference from the main model is that in Case (b) (i.e., when the discount factor δ is relatively large), the low-type artist always has the incentive to mimic the high-type's optimal strategy because the demand loss from charging the high-type artist's optimal price is exactly zero—that is, the increase in buyer 0's willingness-to-pay exactly equals to the price increase. The high-type must charge a higher-than-optimal price to prevent the low-type from mimicking. Therefore, there is no Costless Separating equilibrium in this case, and only the Costly Separating equilibrium exists, as illustrated in Figure 5 (b).

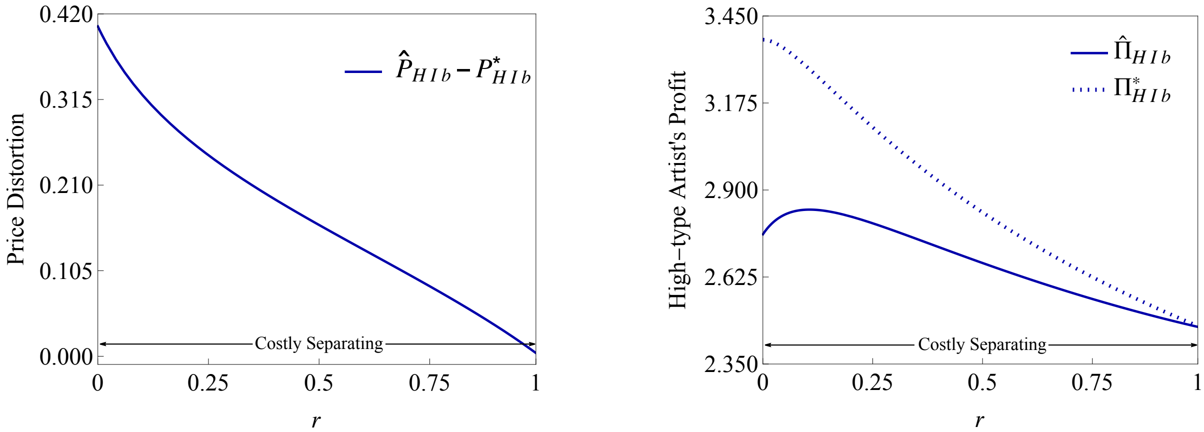
In Case (a) (i.e., when δ is relatively small), the artist sets an interior optimal price that balances royalties from future resales and buyer 0's willingness-to-pay. Similar to the main model, there exists a unique Costly Separating equilibrium when r is relatively small, and a unique Costless Separating equilibrium when r is sufficiently large, as illustrated in Figure 5 (a).

Overall, in both cases, the main findings as well as intuitions from the main model remain: under incomplete information, a higher royalty rate mitigates the high-type artist's price distortion by reducing the low-type artist's mimicking incentive, and thus may improve the high-type artist's profit.

Figure 5: Infinite Resales Opportunities, Incomplete Information: Effect of Royalty Rate on High-type Artist's Price Distortion and Profit



Case (a): $\delta = 0.6, q_H = 1.5, q_L = 1$



Case (b): $\delta = 0.9, q_H = 1.5, q_L = 1$

5.3 Positive Salvage Value of Unsold Artwork

In the main model, we assume that if a seller fails to sell the artwork in a time period, the game ends and she forfeits any remaining value of the artwork. In this extension, we assume that in each resale market $t \geq 1$, if seller t (i.e., buyer $t-1$) fails to sell the artwork to buyer t, the game ends but the seller can continue enjoying the unsold artwork with a salvage value βv_{t-1}, where $\beta \in (0, 1)$ is constant across all sellers (buyers). (Recall that v_{t-1} denotes seller t (i.e., buyer $t-1$)'s consumption value of the artwork within time period $t-1$.)

We first consider the resale market at time $t \geq 1$, where the artwork's popularity type $j \in \{H, L\}$ is public information. Buyer t will purchase if and only if

$$u_{jt} = \theta_t q_j - p_{jt} + \delta V_j(\theta_t) \geq 0,$$

where $V_j(\theta_t)$ denotes buyer t's continuation value from future resale or salvage given her own type θ_t and the type of the artwork $j \in \{H, L\}$. Suppose $\widetilde{\theta}_{jt}$ is the type of buyer t who will be indifferent between purchasing an artwork of type $j \in \{H, L\}$ versus not—that is, $\widetilde{\theta}_{jt} q_j - p_{jt} + \delta V_j(\widetilde{\theta}_{jt}) = 0$. Seller t (i.e., buyer $t-1$) chooses p_{jt} to maximize her expected value $V_j(\theta_{t-1})$, which is equivalent to choosing $\widetilde{\theta}_{jt}$ given the one-to-one mapping between $\widetilde{\theta}_{jt}$ and p_{jt} (i.e., $p_{jt} = \widetilde{\theta}_{jt} q_j + \delta V_j(\widetilde{\theta}_{jt})$):

$$V_j(\theta_{t-1}) = \sup_{0 \leq \widetilde{\theta}_{jt} \leq 1} (1-r)\left(1-\widetilde{\theta}_{jt}\right)\left(\widetilde{\theta}_{jt} q_j + \delta V_j(\widetilde{\theta}_{jt})\right) + \widetilde{\theta}_{jt}\left(\beta \theta_{t-1} q_j\right), \tag{4}$$

where $1 - \widetilde{\theta}_{jt}$ is the probability that the artwork is sold in period t.

We can show that given $r \in [0,1), \delta \in (0,1]$, there exists a unique function $V_j : [0,1] \to \mathrm{R}$ that satisfies equation (4). In other words, $V_j(\cdot)$ given by equation (4) is a contraction mapping and hence there exists a unique fixed point to the equation, which determines a unique equilibrium in resale markets. However, there is no closed-form solution of $V_j(\cdot)$ to equation (4); instead, we can solve $V_j(\cdot)$ for any given (q_j, r, δ) numerically by a standard procedure of value iteration.[10]

Given $V_j(\cdot)$, we can solve for the optimal type of the indifferent buyer t, $\widetilde{\theta}^*_{jt}(\theta_{t-1})$, for any θ_{t-1} according to equation (4). Then, the optimal price set by buyer $t-1$ of type θ_{t-1} is $p^*_{jt}(\theta_{t-1}) = \widetilde{\theta}^*_{jt}(\theta_{t-1}) q_j + \delta V_j(\widetilde{\theta}^*_{jt}(\theta_{t-1}))$, and the transaction probability is $d^*_{jt}(\theta_{t-1}) = 1 - \widetilde{\theta}^*_{jt}(\theta_{t-1})$. We can further calculate the artist's expected total future royalty income $R_j(\cdot)$ as a function of the type of the current owner θ_{t-1} by solving the following equation:

$$R_j(\theta_{t-1}) = \left(1 - \widetilde{\theta}^*_{jt}(\theta_{t-1})\right)\left(r p^*_{jt}(\theta_{t-1}) + \delta \mathrm{E}\left[R_j(\theta) \middle| \theta \geq \widetilde{\theta}^*_{jt}(\theta_{t-1})\right]\right).$$

Figure 6 illustrates seller t's expected payoff from the artwork $V_j(\theta_{t-1})$, resale price $p^*_{jt}(\theta_{t-1})$, transaction probability $d^*_{jt}(\theta_{t-1})$, and the artist's expected royalty income $R_j(\theta_{t-1})$, and benchmarks them against the case with $\beta = 0$. Intuitively, when seller t's type θ_{t-1} gets higher, she enjoys a higher salvage value of the artwork when failing to sell it, which increases her expected payoff from the artwork (Figure 6(a)) and makes her sell it at a higher price (Figure 6(b)), which in turn results in a decline in the equilibrium transaction probability (Figure 6(c)) and a lower expected royalty income for the artist (Figure 6(d)). Compared to the benchmark case with $\beta = 0$, a positive salve value lowers the transaction probability in resale markets as well as the artist's expected royalty income.

Next, we consider the primary market. Under complete information, the artwork type $j \in \{H, L\}$ is publicly known. The artist chooses P_j to maximize her expected profit:

$$\Pi^*_j = \max_{P_j} \left(P_j + \delta \mathrm{E}\left[R_j(\theta_0) \middle| \theta_0 \geq \widetilde{\theta}_0\right]\right) \Pr\left(\theta_0 \geq \widetilde{\theta}_0\right), \tag{5}$$

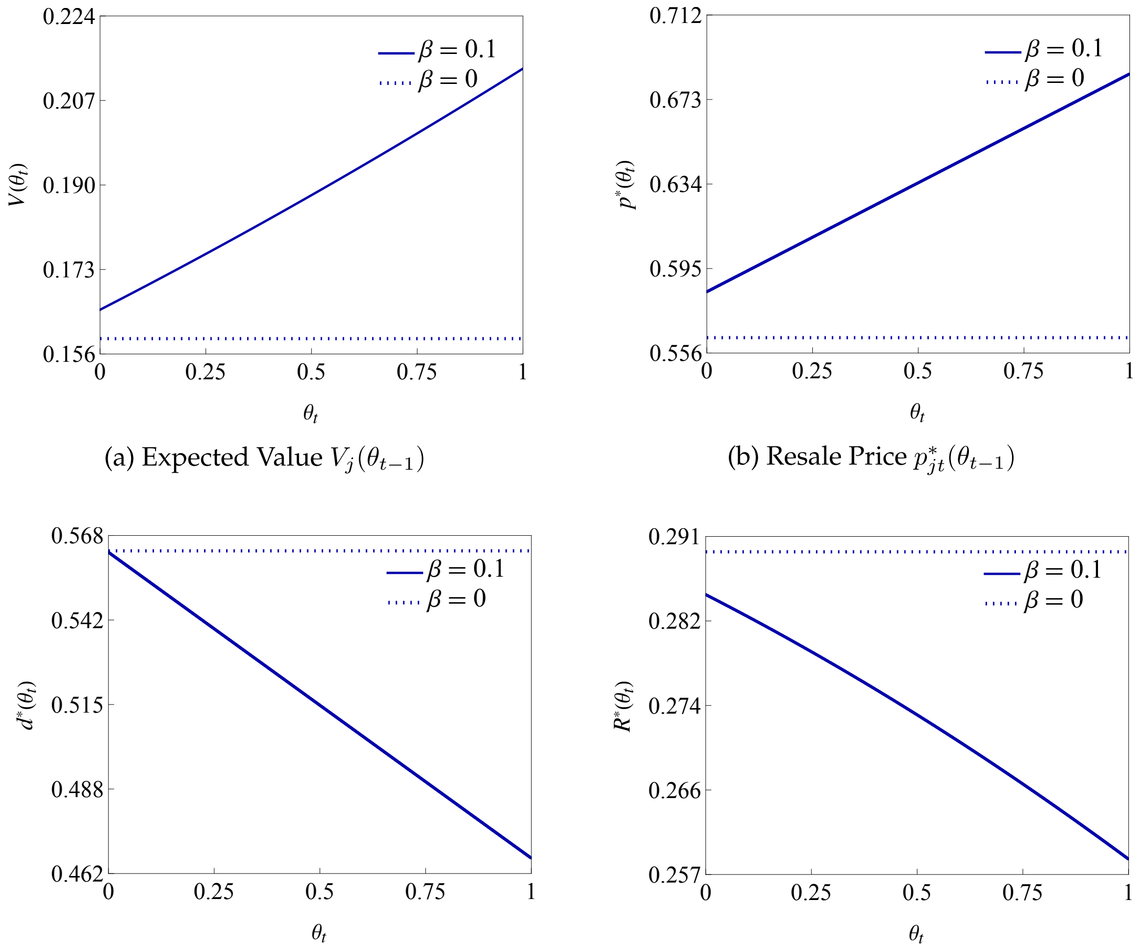
where $\widetilde{\theta}_0$ denotes the type of the indifferent buyer 0 such that $\widetilde{\theta}_0 q_j - P_j + \delta V_j(\widetilde{\theta}_0) = 0$.

Under incomplete information, given the actual type of artwork $j \in \{H, L\}$ and buyer 0's belief $\mu = \Pr(j = H)$, the artist's expected profit as a function of primary market price P is

$$\Pi_j(P; \mu) = \left(P + \delta \mathrm{E}\left[R_j(\theta_0) \middle| \theta_0 \geq \frac{\widetilde{v}_0}{q_j}\right]\right) \Pr\left(\theta_0 \geq \frac{\widetilde{v}_0}{q_j}\right), \tag{6}$$

[10] In particular, we first initialize the value of $V(\theta)$ for all θ on interval $[0,1]$ with a certain step size s. Then, for every θ_{t-1} on the interval, we solve for the optimal $\widetilde{\theta}^*_{jt}(\theta_{t-1})$ according to equation (4) and then calculate $V(\theta_{t-1})$ accordingly. The calculated value of $V(\theta)$ for every $\theta \in [0,1]$ will be used in the next iteration, until convergence is achieved. Convergence is guaranteed by the contraction property.

Figure 6: Positive Salvage Value: Equilibrium Outcome in Resale Market t



(a) Expected Value $V_j(\theta_{t-1})$

(b) Resale Price $p^*_{jt}(\theta_{t-1})$

(c) Transaction Probability $d^*_{jt}(\theta_{t-1})$

(d) Expected Royalty Income $R_j(\theta_{t-1})$

Note: $q_j = 1$, $\delta = 0.8$ and $r = 0.5$.

where $\widetilde{v}_0$ is the valuation of the indifferent buyer 0 such that $\widetilde{v}_0 - P + \delta V_0(\widetilde{v}_0; \mu) = 0$. $V_0(v_0; \mu)$ denotes buyer 0's expected payoff from the artwork given her valuation v_0 and belief μ.

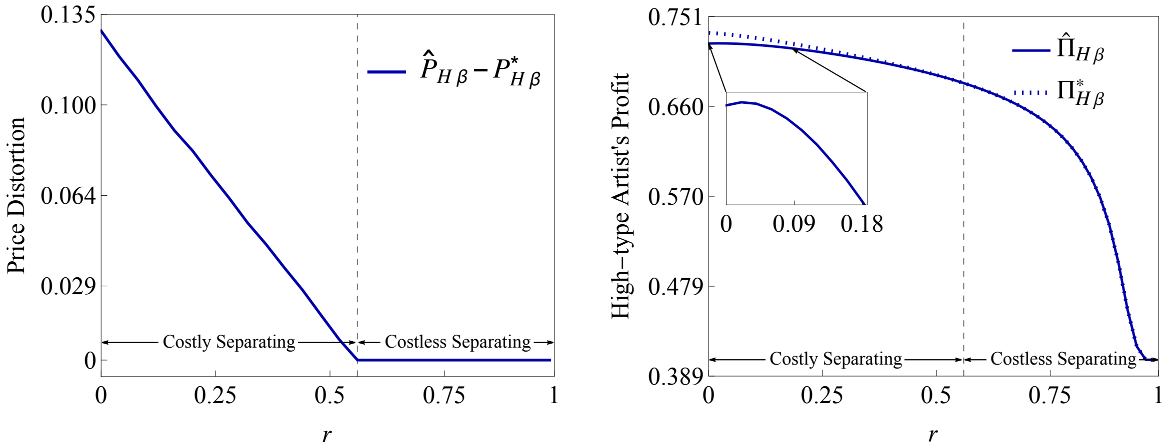
$$\begin{aligned} V_0(v_0;\mu) \quad &= \mu \left\{ \max_{\widetilde{\theta}_{1H}} (1-r)(1-\widetilde{\theta}_{1H}) \left(\widetilde{\theta}_{1H} q_H + \delta V_H(\widetilde{\theta}_{1H}) \right) + \widetilde{\theta}_{1H}(\beta v_0) \right\} \\ &+ (1-\mu) \left\{ \max_{\widetilde{\theta}_{1L}} (1-r)(1-\widetilde{\theta}_{1L}) \left(\widetilde{\theta}_{1L} q_L + \delta V_L(\widetilde{\theta}_{1L}) \right) + \widetilde{\theta}_{1L}(\beta v_0) \right\}, \end{aligned} \tag{7}$$

where $\widetilde{\theta}_{1j}$ is the type of the indifferent buyer 1 in period 1 given the artwork's type $j \in \{H, L\}$.

As mentioned earlier, given (q_j, r, δ), we can numerically calculate $V_j(\theta)$ for all $\theta \in [0, 1]$ and $j \in \{H, L\}$ according to equation (4). Then, we numerically solve for the equilibrium price in the primary market following the same procedure as in the main model, according to equation (6) and equation (7).

In Figure 7, we illustrate the effect of royalty rate r on high-type artist's price distortion and profit. When r is large, a Costless Separating equilibrium exists, in which the artist charges

Figure 7: Positive Salvage Value: Effect of Royalty Rate on High-Type Artist's Price Distortion and Profit



(a) High-Type's Price Distortion

(b) High-Type's Profit

Note. We assume $q_H = 1.5, q_L = 1, \delta = 0.8, \beta = 0.1$ in this numerical illustration. We take the value of r on interval $[0, 1]$ with step size 0.2. In panel (b), we zoom into the high-type artist's profit under incomplete information when r is relatively small, which highlights that there exists an interval $(0, r')$ where the high-type's profit increases with r.

the same price under complete information and thus price distortion is zero. In contrast, when r is small, a costly equilibrium arises. In this case, the low-type artist changes the optimal price under complete information $P^*_{L\beta}$, while the high-type artist charges a price higher than that under complete information $\widehat{P}_{H\beta} > P^*_{H\beta}$ (the subscript β represents this extension with positive salvage value). The same as in the main model, a higher royalty rate can reduce the high-type artist's price distortion and thus improve her profit under incomplete information.

5.4 Endogenous Popularity in Resale Markets and Belief Cascade

In the main model, we assume that the artwork's popularity type j becomes public information in resale markets. As a result, the artist's pricing strategy only affects buyer 0's belief in the primary market and has no impact on resale markets. In this extension, we aim to model the long-lasting effect of the artist's pricing strategy such that it affects buyers' beliefs in both primary and resale markets. To this end, we assume that the artwork's popularity type in the primary market is still determined by nature and remains as the artist's private information, the same as in the main model. In resale markets, the artwork's popularity type arises endogenously. In particular, we model buyer 0 as an opinion leader such that all buyers in resale markets will adopt the same belief as buyer 0. In other words, we consider a beauty contest setup for resale markets with buyer 0 as the coordination device. In fact, as long as all other buyers in the resale markets adopt buyer 0's belief as the true popularity type, it is of each individual buyer's incentive to follow suit by adopting the same view. To summarize, the artist uses the price as a signal to influence buyer 0's inference of the artwork popularity in the primary market; buyer 0, as an opinion leader, then honestly discloses her belief μ to all buyers in the resale markets.[11] We call this "belief cascade".

Under complete information, buyer 0's belief is always equal to the true type of artwork, so the equilibrium outcome is identical to that in the main model. We focus on the incomplete information case below.

Proposition 10 (Belief Cascade, Incomplete Information). *Suppose the artwork's popularity is the artist's private information, and all buyers on resale markets hold the same belief as buyer* 0*. In the primary market, the unique equilibrium that survives the intuitive criterion is the following separating equilibrium:*

1. *(**Costless Separating**) if* $q_H/q_L \geq k_C(\delta, r)$*, the artist charges the same price as under complete information* $P_j^* = \frac{[1-\alpha(\delta,r)]q_j}{1+\sqrt{1-\delta(1-r)}}$ *for* $j \in \{H, L\}$*; (the subscript* C *represents this extension with belief cascade)*
2. *(**Costly Separating**) if* $q_H/q_L < k_C(\delta, r)$*, the high-type artist charges a higher price than under complete information,* $\widehat{P}_{HC} > P_H^*$*, and the low-type artist charges the same price as under complete information* $P_L^* = \frac{[1-\alpha(\delta,r)]q_L}{1+\sqrt{1-\delta(1-r)}}$*. The high-type artist's price is higher than that in the main model,* $\widehat{P}_{HC} > \widehat{P}_H$*.*
3. *A higher royalty rate* r *lowers the high-type artist's price distortion and profit in equilibrium.*

The off-equilibrium-path belief can be specified as $\mu(P') = 0$ *for all off-equilibrium-path price* P'*.*

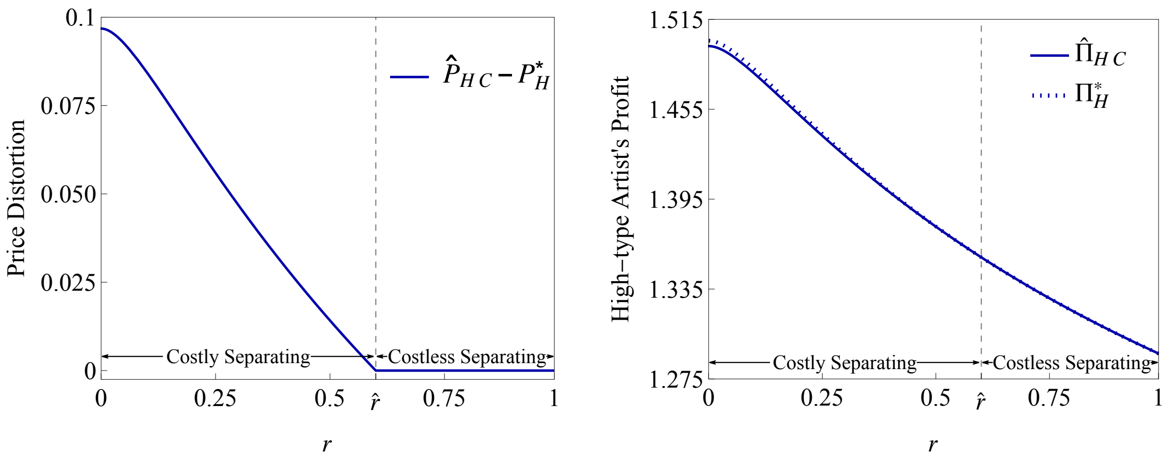
Figure 8 illustrates the high-type artist's price distortion and profit in equilibrium. Compared to the main model, a key distinction in this extension is that the high-type artist's profit monotonically decreases with the royalty rate in equilibrium. The intuition is as follows. In this extension, by mimicking the high-type artist, the low-type artist can not only improve buyer 0's belief, but also the belief of all buyers in the resale markets and thus the expected royalty income from resale markets. Therefore, the low-type artist has a stronger incentive to mimic the high-type compared to the main model. Recall that in the main model, the reason a higher royalty rate can increase the high-type artist's profit is that it suppresses the low-type artist's mimicking incentives, thereby making it easier for the high-type to separate (intuition under Proposition 5). This effect is weakened here because a higher royalty rate amplifies the difference between the high-type and low-type's expected royalty income, which strengthens the low-type artist's mimicking incentives. As a result, the high-type artist's profit decreases with the royalty rate.

5.5 Fluctuating Popularity

In the main model, the popularity type of an artwork remains constant over time. In reality, buyers in different generations may have different aesthetic judgments of art. This motivates us to study a scenario in which the popularity type of the artwork fluctuates over time. In particular, we assume that given the artwork's type $j \in \{H, L\}$ at time $t \geq 0$, it remains as type j at time $t+1$ with probability $\sigma \in [1/2, 1]$ and transitions to type $-j$ with probability

[11] Buyer 0's honest disclosure can be out of reputation concerns.

Figure 8: Belief Cascade: High-type Artist's Price Distortion and Profit



(a) High-Type Artist's Price Distortion

(b) High-Type Artist's Profit

Note. $q_H = 2.6, q_L = 1, \delta = 0.9$.

$1 - \sigma$, where $-j \neq j \in \{H, L\}$. The popularity of the artwork is still assumed to be public information in all resale markets.

In each resale market $t \geq 1$, suppose the popularity type of the artwork is type j in this period. Buyer t will purchase if and only if $u_{jt} = \theta_t q_j - p_{jt} + \delta(1-r)\left(\sigma\pi_{j,t+1} + (1-\sigma)\pi_{-j,t+1}\right) \geq 0$, which implies,

$$d_{jt} = 1 - \frac{p_{jt} - \delta(1-r)\left(\sigma\pi_{j,t+1} + (1-\sigma)\pi_{-j,t+1}\right)}{q_j}. \tag{8}$$

Seller t (i.e., buyer $t-1$) chooses p_{jt} to maximize her expected resale payoff:

$$p^*_{jt} = \arg\max_{p_{jt}} (1-r) p_{jt} d_{jt} = \frac{1}{2}\left(q_j + \delta(1-r)\left(\sigma\pi_{j,t+1} + (1-\sigma)\pi_{-j,t+1}\right)\right), \tag{9}$$

and correspondingly,

$$\pi^*_{jt} = \frac{\left(q_j + \delta(1-r)\left(\sigma\pi_{j,t+1} + (1-\sigma)\pi_{-j,t+1}\right)\right)^2}{4q_j}. \tag{10}$$

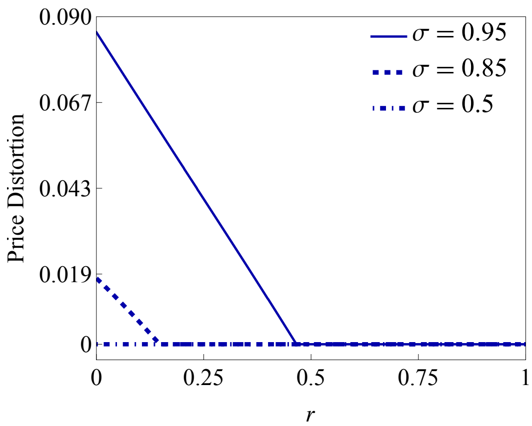
Given the time-stationarity of the problem, we have $\pi^*_{j,t} = \pi^*_{j,t+1} \equiv \pi^*_j$ for $j \in \{H, L\}$. Plugging in this to equation (10), we get two quadratic equations in terms of π^*_H, π^*_L, which however, do not admit analytical solutions. We solve for π^*_H, π^*_L numerically. Then d^*_j and p^*_j can be calculated using Equations (8) and (9). Denote R^*_j as the expected royalty income in equilibrium given the artwork's current type j. We have,

$$R^*_j = r\pi^*_j + \delta d^*_j(\sigma R^*_j + (1-\sigma) R^*_{-j}), \text{ for } j \neq -j \in \{H, L\},$$

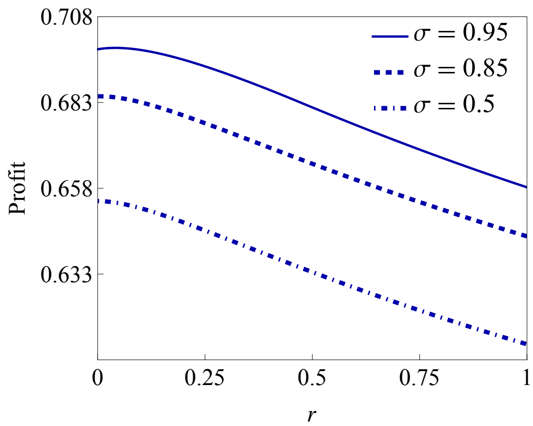
which can be combined to solve for R^*_j, $j \in \{H, L\}$.

In the primary market, the analysis is the same as in the main model except that buyer 0's expected resale value from an artwork of type j is $\sigma\pi^*_j + (1-\sigma)\pi^*_{-j}$, and the j-type artist's expected royalty income becomes $\sigma R^*_j + (1-\sigma) R^*_{-j}$. Figure 9 provides a numerical demonstration of the high-type artist's price distortion and profit under different values of σ. We can see that the findings from our main model still persist: the high-type artist's price distortion still declines with r, and her profit first increases and then decreases with r under incomplete information.

Figure 9: Fluctuating Popularity: High-type Artist's Price Distortion and Profit



(a) High-Type Artist's Price Distortion



(b) High-Type Artist's Profit

Note. The numerical solution is based on parameter values $\delta = 0.8, q_H = 1.5, q_L = 1$. We take values of r from $[0, 1]$ with step size of 0.001.

A special case noteworthy is when $\sigma = 1/2$, only Costless Separating equilibrium exists and the price distortion is zero. This is because when $\sigma = 1/2$, the artwork's popularity type becomes a purely random walk with no past dependence. As a consequence, the artwork's actual popularity type j at time 0 has no influence on buyer 0's expected resale value, which eliminates the low-type artist's mimicking incentives, and the model degenerates to the complete information case.

6 Concluding Remarks

In this paper, we examine how royalties may influence artists' pricing decisions and market efficiency, providing important insights for art markets. We show that when there is no information asymmetry between artists and buyers (e.g., established artists), enforcing royalties lowers artworks' resale value and transaction volume, reduces artists' profits, and makes all market participants worse off. When artists possess superior information about their artworks' market appeal compared to buyers (e.g., emerging artists), those with popular appeal may set inefficiently high prices to signal their popularity, harming primary market efficiency. In such cases, a positive but moderate royalty rate mitigates price distortion for these popular artists, increasing both their profits and social welfare. We also explore several extensions that demonstrate the robustness and boundaries of our findings.

As a first attempt to investigate the impact of royalties on the art market, we build a relatively simple model. While we believe our model captures the key mechanism of how royalties affect artists' pricing decisions and the art market efficiency, we acknowledge there are several limitations. First, we assume that the artist is risk-neutral. Royalties allow artists to smooth their income and consumption, which brings an extra benefit when artists are risk-averse. Second, by assuming all agents are rational in our model, we do not attempt to account for the potential fairness concerns of artists, which could further exacerbate the low transaction probability in the absence of royalties and thus strengthen the trade-facilitating role of royalties. Third, royalties are assumed to be a fixed percentage of the resale price in our model, which is consistent with the current industry practice. In theory, one could explore a more general class of royalty contracts. For example, royalties could be set at a fixed level, or as a percentage of the resale gain (i.e., the difference between the selling and buying prices). It would then be interesting to investigate the optimal royalty contract. Lastly, we focus on a monopolistic artist, without considering the competition among artists. Royalties depress secondary markets for sold artworks and thus may facilitate the primary market for new artworks. We leave all these as interesting future research directions.

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Appendix

Proof of Proposition 1: Complete Information

Proof. By substituting $\pi_{j,t+1} = \pi^*_{jt} \equiv \pi^*_j$ to equation (3), we have

$$[\delta(1-r)\pi^*_j]^2 - 2[2-\delta(1-r)]q_j\pi^*_j + q_j^2 = 0,$$

which has two roots $\pi^*_j = q_j/[1 \pm \sqrt{1-\delta(1-r)}]^2$. Notice that by definition, $d_{jt}(p^*_{jt}) \leq 1$, or equivalently, $\pi^*_j \leq q_j/[\delta(1-r)]$, which pins down $\pi^*_j = q_j/[1+\sqrt{1-\delta(1-r)}]^2$ as the only plausible solution. Correspondingly, $p^*_j = (q_j + \delta(1-r)\pi^*_j)/2 = q_j/[1+\sqrt{1-\delta(1-r)}]$ and $d^*_j = 1/[1+\sqrt{1-\delta(1-r)}]$. The optimal price in the primary market can be solved by the first-order condition. The comparative statics can be proved by the following.

$$\begin{aligned}
\frac{dp^*_j}{dr} &= -\frac{\delta q_j}{2\sqrt{1-(1-r)\delta}[1+\sqrt{1-(1-r)\delta}]^2} < 0,\\
\frac{dd^*_j}{dr} &= -\frac{\delta}{2\sqrt{1-(1-r)\delta}[1+\sqrt{1-(1-r)\delta}]^2} < 0,\\
\frac{d\pi^*_j}{dr} &= -\frac{\delta q_j}{\sqrt{1-(1-r)\delta}[1+\sqrt{1-(1-r)\delta}]^3} < 0,\\
\frac{dP^*_j}{dr} &= -\frac{\delta\{4(1-\delta)[2-\delta+2\sqrt{1-(1-r)\delta}] + \delta r(4-\delta)\}q_j}{4\sqrt{1-(1-r)\delta}[1+\sqrt{1-(1-r)\delta}]^2[1-\delta+\sqrt{1-(1-r)\delta}]^2} < 0,\\
\frac{dD^*_j}{dr} &= -\frac{\delta r[1-\sqrt{1-(1-r)\delta}]^2}{4(1-r)^2\sqrt{1-(1-r)\delta}[1-\delta+\sqrt{1-(1-r)\delta}]^2} < 0,\\
\frac{d\Pi^*_j}{dr} &= \frac{2[1+\alpha(\delta,r)]q_j}{1+\sqrt{1-(1-r)\delta}}\frac{dD^*_j}{dr} < 0,\\
\frac{dSW_j}{dr} &= \left[q_j(1-D^*_j) + \frac{\delta(1-(1-d^*_j)^2)q_j}{2(1-\delta d^*_j)}\right]\frac{dD^*_j}{dr} + \frac{[2\delta(1-d^*_j)+(\delta d^*_j)^2]D^*_j q_j}{2(1-\delta d^*_j)^2}\frac{dd^*_j}{dr} < 0.
\end{aligned}$$

□

Proof of Lemma 1: No Pooling Equilibrium

Proof. The proof is a special case of that to Lemma A1 with $r = 0$ and thus omitted. □

Proof of Proposition 2: Incomplete Information without Royalties

Proof. The proof is a special case of that to Proposition 3 with $r = 0$ and thus omitted. □

Proof of Proposition 3: Incomplete Information with Royalties

For convenience, we denote $\overline{\pi}(\mu) = \mu\pi^*_H + (1-\mu)\pi^*_L$ as the buyer 0's expected resale value under belief μ, and $\gamma(\delta, r) = \sqrt{1-(1-r)\delta}$ in the following proof. To begin with, we prove that no pooling equilibrium can survive the intuitive criterion.

Lemma A1. *Under incomplete information with royalties, there does not exist a pooling equilibrium that survives the intuitive criterion.*

Proof. We prove the lemma by contradiction. Suppose a pooling equilibrium exists.

First, we characterize the buyer 0's purchasing decision and transaction probability in the primary market. Given the belief λ, the buyer 0 can update beliefs based on the private match value v_{j0}. According to Bayes' rule, the buyer 0's posterior belief is:

$$\Pr(q_j = q_H | v_{j0}) = \begin{cases} \overline{\lambda} & \text{if } 0 \le v_{j0} \le q_L, \\ 1 & \text{if } q_L < v_{j0} \le q_H, \end{cases}$$

where $\overline{\lambda} = \overline{\lambda}(\lambda) = \lambda q_L / [\lambda q_L + (1-\lambda) q_H]$.

For the low-type artist, buyer 0's posterior belief based on the match value v_{j0} is always $\overline{\lambda}$, so buyer 0 will purchase if and only if $\theta_0 q_L - P + \delta(1-r)\overline{\pi}(\overline{\lambda}) \ge 0$, which implies that the low-type artist's transaction probability is

$$D_L(P;\lambda) = \begin{cases} 1 & 0 \le P < \delta(1-r)\overline{\pi}(\overline{\lambda}) \\ 1 - \frac{P - \delta(1-r)\overline{\pi}(\overline{\lambda})}{q_L} & \text{if } \delta(1-r)\overline{\pi}(\overline{\lambda}) \le P < \delta(1-r)\overline{\pi}(\overline{\lambda}) + q_L, \\ 0 & \text{otherwise.} \end{cases} \tag{A1}$$

For the high-type artist, let us consider two cases. First, if $0 \le \theta_0 \le q_L/q_H$, then $v_{j0} = \theta_0 q_H \le q_L$ and $\Pr(q = q_H | v_{j0}) = \overline{\lambda}$, which implies that the buyer 0 will purchase if and only if $\theta_0 q_H - P + \delta(1-r)\overline{\pi}(\overline{\lambda}) \ge 0 \Leftrightarrow \theta_0 \ge \overline{\theta}_H \equiv (P - \delta(1-r)\overline{\pi}(\overline{\lambda}))/q_H$. Second, if $q_L/q_H < \theta_0 \le 1$, then $v_{j0} = \theta_0 q_H > q_L$ and $\Pr(q_j = q_H | v) = 1$, which means that the buyer 0 will purchase if and only if $\theta_0 q_H - P + \delta(1-r)\pi_H^* \ge 0 \Leftrightarrow \theta_0 \ge (P - \delta(1-r)\pi_H^*)/q_H$. Combining these two cases, we have the high-type artist's transaction probability as follows.

$$\begin{aligned} & D_H(P;\lambda) \\ &= \Pr\left(\theta_0 \le \frac{q_L}{q_H}\right) \Pr\left(\theta_0 \ge \bar{\theta}_H \middle| \theta_0 \le \frac{q_L}{q_H}\right) + \Pr\left(\theta_0 > \frac{q_L}{q_H}\right) \Pr\left(\theta_0 \ge \frac{P - \delta(1-r)\pi_H^*}{q_H} \middle| \theta_0 > \frac{q_L}{q_H}\right) \\ &= \begin{cases} 1 & 0 \le P < \delta(1-r)\overline{\pi}(\overline{\lambda}) \\ 1 - \frac{P - \delta(1-r)\overline{\pi}(\overline{\lambda})}{q_H} & \text{if } \delta(1-r)\overline{\pi}(\overline{\lambda}) \le P < \delta(1-r)\overline{\pi}(\overline{\lambda}) + q_L, \\ 1 - \frac{q_L}{q_H} & \text{if } \delta(1-r)\overline{\pi}(\overline{\lambda}) + q_L \le P < \delta(1-r)\pi_H^* + q_L, \\ 1 - \frac{P - \delta(1-r)\pi_H^*}{q_H} & \text{if } \delta(1-r)\pi_H^* + q_L \le P \le \delta(1-r)\pi_H^* + q_H, \\ 0 & \text{otherwise.} \end{cases} \end{aligned} \tag{A2}$$

Second, suppose there exists a pooling equilibrium with price $\widetilde{P}$, which must be $\widetilde{P} < \delta(1-r)\overline{\pi}(\overline{\lambda}) + q_L$; otherwise the low-type artist has zero profit and thus will deviate. We need to consider two cases.

(i) For $0 \le \widetilde{P} < \delta(1-r)\overline{\pi}(\overline{\lambda})$, the two types of artists' profits are

$$\Pi_L(\widetilde{P};\lambda) = \widetilde{P} + \frac{2\alpha}{1+\gamma} q_L, \text{and } \Pi_H(\widetilde{P};\lambda) = \widetilde{P} + \frac{2\alpha}{1+\gamma} q_H.$$

We consider an off-equilibrium-path price $P_o > \delta(1-r)\pi_H^* > \widetilde{P}$ such that $\Pi_L(P_o;1) = \Pi_L(\widetilde{P};\lambda)$, then we have

$$\Pi_H(P_o, 1) - \Pi_H(\widetilde{P}, \lambda) = \frac{q_H - q_L}{q_H q_L} P_o \left[P_o - \delta(1-r)\pi_H^*\right] > 0.$$

Therefore, $P' = P_o + \epsilon$ with sufficiently small $\epsilon > 0$ satisfies $\Pi_L(P'; 1) < \Pi_L(\widetilde{P}; \lambda)$ and $\Pi_H(P'; 1) > \Pi_H(\widetilde{P}; \lambda)$, which violates the intuitive criterion.

(ii) For $\delta(1-r)\overline{\pi}(\overline{\lambda}) \leq \widetilde{P} < \widetilde{P} < \delta(1-r)\overline{\pi}(\overline{\lambda}) + q_L$, the two types of artists' profits are

$$\Pi_L(\widetilde{P}; \lambda) = \left(\widetilde{P} + \frac{2\alpha}{1+\gamma} q_L\right)\left(1 - \frac{\widetilde{P} - \delta(1-r)\overline{\pi}(\overline{\lambda})}{q_L}\right),$$

$$\text{and } \Pi_H(\widetilde{P}; \lambda) = \left(\widetilde{P} + \frac{2\alpha}{1+\gamma} q_H\right)\left(1 - \frac{\widetilde{P} - \delta(1-r)\overline{\pi}(\overline{\lambda})}{q_H}\right).$$

We consider an off-equilibrium-path price $P_o > \widetilde{P}$ such that $\Pi_L(P_o; 1) = \Pi_L(\widetilde{P}; \lambda)$, then we have

$$\begin{aligned}\Pi_H(P_o; 1) - \Pi_H(\widetilde{P}; \lambda) =& (\Pi_H(P_o; 1) - \Pi_L(P_o; 1)) - (\Pi_H(\widetilde{P}; \lambda) - \Pi_L(\widetilde{P}; \lambda)) \\ =& \frac{q_H - q_L}{q_H}\left[(P_o - \widetilde{P})\left(1 - \frac{2\alpha}{1+\gamma}\right) + \frac{2\alpha}{1+\gamma}\delta(1-r)(\overline{\pi}(1) - \overline{\pi}(\overline{\lambda}))\right] > 0,\end{aligned}$$

where the ">" is due to $P_o > \widetilde{P}$ and $\overline{\pi}(1) > \overline{\pi}(\overline{\lambda})$.

Therefore, $P' = P_o + \epsilon$ with sufficiently small $\epsilon > 0$ satisfies $\Pi_L(P'; 1) < \Pi_L(\widetilde{P}; \lambda)$ and $\Pi_H(P'; 1) > \Pi_H(\widetilde{P}; \lambda)$, which violates the intuitive criterion. □

Next, we prove the existence and the uniqueness of separating equilibrium.

Proof. (i) We prove that the equilibrium prices constitute a PBE. In any separating equilibrium, the low-type artist charges the optimal price under complete information P_L^*. The high-type artist's price P_H must satisfy $\Pi_L(P_H; 1) \leq \Pi_L(P_L^*; 0)$; otherwise, the low-type artist will mimic the high-type artist's equilibrium strategy. If the optimal price under complete information can constitute a separating equilibrium, we have

$$\Pi_L(P_H^*; 1) \leq \Pi_L(P_L^*; 0) \Leftrightarrow \frac{q_H}{q_L} \geq k(\delta, r) \equiv \frac{2r\delta}{(2+r)\delta - 2(1+\gamma)} + \frac{2(1-\gamma) - \delta(2-r)(1-r)}{\delta r(1-r) - 2\gamma^2(1-\gamma)}.$$

Otherwise, if $q_H/q_L < k(\delta, r)$, we must have $\Pi_L(P_H; 1) \leq \Pi_L(P_L^*; 0)$, which is equivalent to

$$P_H \geq \widehat{P}_H = \frac{(1-\gamma)(q_H + q_L) + 2(\gamma - \alpha)q_L + \sqrt{(1-\gamma)(q_H - q_L)[(1-\gamma)q_H + (4\alpha + \gamma + 3)q_L]}}{2(1+\gamma)}$$

$$\text{or } P_H \leq \widehat{P}''_H = \frac{(1-\gamma)(q_H + q_L) + 2(\gamma - \alpha)q_L - \sqrt{(1-\gamma)(q_H - q_L)[(1-\gamma)q_H + (4\alpha + \gamma + 3)q_L]}}{2(1+\gamma)},$$

where $\widehat{P}_H > P_H^*$. This means that the low-type artist does not mimic the high-type artist.

Next, we show that for any off-equilibrium-path price, neither type can make a profitable deviation under the specified off-equilibrium-path belief. The low-type artist cannot make any strictly profitable deviation under belief $\mu = 0$. For the high-type artist, if $q_H/q_L \geq k(\delta, r)$, the equilibrium price is the optimal one under complete information, and thus high-type artist does not deviate. If $q_H/q_L < k(\delta, r)$, we can show that $\Pi_H(\widehat{P}_H; 1) \geq \max_{P_H} \Pi_H(P_H; 0)$. Following the transaction probability in equation (A2), the high-type artist's profit under belief $\lambda = 0$ is

$$\Pi_H(P_H;0) = \begin{cases} \left(P_H + \frac{2\alpha}{1+\gamma} q_H\right)\left(1 - \frac{P_H - \delta(1-r)\pi_L^*}{q_H}\right) & \text{if } 0 \leq P_H < \delta(1-r)\pi_L^* + q_L, \\ \left(P_H + \frac{2\alpha}{1+\gamma} q_H\right)\left(1 - \frac{q_L}{q_H}\right) & \text{if } \delta(1-r)\pi_L^* + q_L \leq P_H < \delta(1-r)\pi_H^* + q_L, \\ \left(P_H + \frac{2\alpha}{1+\gamma} q_H\right)\left(1 - \frac{P_H - \delta(1-r)\pi_H^*}{q_H}\right) & \text{if } \delta(1-r)\pi_H^* + q_L \leq P_H \leq \delta(1-r)\pi_H^* + q_H. \end{cases}$$

For $\delta(1-r)\pi_H^* + q_L \leq P_H \leq \delta(1-r)\pi_H^* + q_H$, we have

$$\frac{d\Pi_H(P_H;0)}{dP_H} \leq \frac{2}{q_H}\left(\frac{\gamma - \alpha}{1+\gamma} q_H - q_L\right) < \frac{2q_L}{q_H}\left(\frac{\gamma-\alpha}{1+\gamma} k - 1\right) < 0,$$

where the "$\leq$" is obtained by substituting $P_H = \delta(1-r)\pi_H^* + q_L$. This means that $\delta(1-r)\pi_H^* + q_L$ is the unique local maximizer of $\Pi_H(P_H;0)$ for $P_H \geq \delta(1-r)\pi_L^* + q_L$. We also have $\widehat{P}_H < [\delta(1-r)\pi_H^* + q_L]$. Given the quadratic form of $\Pi_H(P_H, 1)$ and $\Pi_H(\delta(1-r)\pi_H^* + q_L; 0) = \Pi_H(\delta(1-r)\pi_H^* + q_L; 1)$, we have

$$\Pi_H(\widehat{P}_H; 1) \geq \Pi_H(\delta(1-r)\pi_H^* + q_L; 1) = \Pi_H(\delta(1-r)\pi_H^* + q_L; 0).$$

For $0 \leq P_H < \delta(1-r)\pi_L^* + q_L$, we have $\Pi_H(P_H; 0) \leq \frac{1}{4q_H}\left[q_H + \delta(1-r)\pi_L^* + \frac{2\alpha}{1+\gamma} q_H\right]^2$ due to its quadratic form. It suffices to show

$$\begin{aligned} &\Pi_H(\widehat{P}_H; 1) - \frac{1}{4q_H}\left[q_H + \delta(1-r)\pi_L^* + \frac{2\alpha}{1+\gamma} q_H\right]^2 \\ &= \left(1 - \frac{q_L}{q_H}\right)\left\{\left(1 - \frac{2\alpha}{1+\gamma}\right)\widehat{P}_H - \frac{[4\alpha^2 - 4(3-\gamma)\alpha + (1+\gamma)^2]q_H + [4\alpha^2 - 8\gamma\alpha + (1+\gamma)(3-\gamma)]q_L}{4(1+\gamma)^2}\right\} \\ &> \left(1 - \frac{q_L}{q_H}\right)\frac{4\alpha^2 - 8\alpha\gamma + (3-\gamma)(1+\gamma)}{4(1+\gamma)^2}(q_H - q_L) \\ &> \left(1 - \frac{q_L}{q_H}\right)\frac{4\alpha^2 + (1-\gamma)(1+\gamma)}{4(1+\gamma)^2}(q_H - q_L) > 0, \end{aligned}$$

where the first "$>$" is due to $\widehat{P}_H > P_H^*$.

(ii). We prove the uniqueness of the equilibrium by contradiction. Suppose there exists another separating equilibrium $\{P_H, P_L\}$ that survives the intuitive criterion. In any separating equilibrium, the high-type artist's price should satisfy $P_H > \widehat{P}_H$ or $P_H \leq \widehat{P}''_H$; otherwise, the low-type artist can profitably mimic the high-type artist's equilibrium strategy.

If $q_H/q_L \geq k(\delta, r)$, for any equilibrium price $P_H \neq P_H^* \geq \widehat{P}_H$, we consider an off-equilibrium-path price P_H^*, the low-type artist cannot make a profitable deviation to P_H^*, but the high-type artist can achieve the optimal profit under $\mu = 1$. Based on the intuitive criterion, the high-type artist can benefit from deviating to P_H^* under the only reasonable belief $\mu = 1$.

If $q_H/q_L < k(\delta, r)$, let us consider two cases. First, if $P_H > \widehat{P}_H$, for an off-equilibrium-path price $P' = \widehat{P}_H + \epsilon$ with sufficiently small $\epsilon > 0$, the low-type artist cannot make any profitable deviation under any belief, but the high-type artist can make profitable deviation under $\mu = 1$.

Consequently, such equilibrium fails the intuitive criterion. Second, if $P_H \le \widehat{P}''_H$, we consider an off-equilibrium-path price $P' = \widehat{P}_H + \epsilon$ with sufficiently small $\epsilon > 0$, the high-type artist can benefit from deviation since $\Pi_H(\widehat{P}_H; 1) > \Pi_H(P_H; 1)$ for all $P_H \le \widehat{P}''_H$, while the low-type artist cannot benefit from deviating to P'. Thus, such equilibria fail the intuitive criterion.

(iii) We show that the specified belief survives the intuitive criterion. Notice that in order to fail the intuitive criterion, if the low-type artist is not willing to deviate to P' under any possible belief, then the high-type artist should make a profitable deviation when buyer 0 perceives the artist as the high-type. Equivalently, we only need to show that for any off-equilibrium-path price P', the low-type artist is willing to deviate under the most optimistic belief $\mu = 1$, or the high-type artist cannot make a profitable deviation even if it is perceived as the high-type.

If $q_H/q_L \ge k(\delta, r)$, the high-type artist sets the optimal price under complete information and thus does not want to deviate under any belief, we can specify $\mu(P') = 0$ for any off-equilibrium-path price P'.

If $q_H/q_L < k(\delta, r)$, for off-equilibrium-path price $P' < \widehat{P}_H$, the low-type artist can make profitable deviation under the most optimistic belief. For any off-equilibrium-path price $P' > \widehat{P}_H$, the high-type artist cannot make any profitable deviation under any beliefs, and low-type artist doesn't deviate even under $\mu = 1$, so we can specify belief as $\mu = 0$ for convenience.

(i), (ii), and (iii) together complete the equilibrium characterization. Next, we prove the comparative statics of $k(\delta, r)$.

$$\frac{\partial k(\delta,r)}{\partial r} = -\frac{2\delta[2(1-\delta)(1+\gamma)+r\delta]}{[(2+r)\delta-2(1+\gamma)]^2\gamma} - \frac{\delta^3 r(1-r)^2(\gamma-r)^2(1-\gamma)^2}{\gamma(1-r)^2(1-\delta+\gamma)^2[2(1-\gamma)-(1-r)\delta(2+r-2\gamma)]^2}$$
$$<0.$$
$$\frac{\partial k(\delta,r)}{\partial \delta} = \frac{(1-r)\delta^2 W(\delta)}{\gamma[2-(2+r)\delta+2\gamma]^2[(1-r)\delta(2+r-2\gamma)-2(1-\gamma)]^2},$$

where $W(\delta) \equiv (1-r)^2(-r^3+6r^2-4r+8)\delta^2 - 2(1-r)[r^4-2(2+\gamma)r^3+33r^2-2(1+8\gamma)r+8]\delta + 4(1+\gamma)r^4 - 32\gamma r^3 + (60-12\gamma)r^2 - 32\gamma r + 8$. We need to show $W(\delta) > 0$. We have

$$W'''(\delta) = -\frac{3r(1-r)^4[8(1-\delta)+r(5-r-r\delta)]}{2[1-(1-r)\delta]^{\frac{5}{2}}} < 0,$$

which implies that $W''(\delta) \ge W''(1) = (1-r)^2(1-\sqrt{r})^2(-8r\sqrt{r}-2r^2-2r+11\sqrt{r}+16) > 0$. This means that $W'(\delta) \le W'(1) = -2(1-\sqrt{r})^4 r(2r\sqrt{r}+5r+13\sqrt{r}+10) < 0$, which implies $W(\delta) \ge W(1) = (1-\sqrt{r})^4 r^2(r+4\sqrt{r}+12) > 0$. □

Proof of Proposition 4: Effect of Royalties on Prices and Price Distortion

Proof. If $q_H/q_L < 1/\sqrt{1-\delta}$ and $0 < r < \widehat{r}$, we have

$$\frac{d(\widehat{P}_H - P_H^*)}{dr}$$
$$= \frac{(q_H-q_L)}{2}\left\{\frac{d}{dr}\left(\frac{2\alpha}{1+\gamma}\right) + \frac{[(1-\gamma)(q_H-q_L)+2(1+\alpha)q_L]\frac{d}{dr}(\frac{1-\gamma}{1+\gamma}) + 2(1-\gamma)q_L\frac{d}{dr}(\frac{1+\alpha}{1+\gamma})}{\sqrt{[(1-\gamma)(q_H-q_L)+2(1+\alpha)q_L]^2 - 4(1+\alpha)^2 q_L^2}}\right\}$$

$$<\frac{(q_H-q_L)}{2}\left[\frac{d}{dr}\left(\frac{2\alpha}{1+\gamma}\right)+\frac{d}{dr}\left(\frac{1-\gamma}{1+\gamma}\right)\right]=-\frac{r\delta(1-\gamma)^2(q_H-q_L)}{4(1-r)^2\gamma(1-\delta+\gamma)^2}\leq 0,$$

where the " $<$ " is because $\frac{d}{dr}(\frac{1-\gamma}{1+\gamma})<0$ and $\frac{d}{dr}(\frac{1+\alpha}{1+\gamma})<0$. This also implies that

$$\frac{d\widehat{P}_H}{dr}=\frac{d(\widehat{P}_H-P_H^*)}{dr}+\frac{dP_H^*}{dr}<0.$$

□

Proof of Proposition 5: Effect of Royalties on Artist Profit

Proof. If $q_H/q_L<1/\sqrt{1-\delta}$ and $0\leq r<\widehat{r}$, we have

$$\widehat{\Pi}_H=\Pi_H(\widehat{P}_H,1)=\frac{1}{q_H}\left[\left(\frac{1+\alpha}{1+\gamma}\right)^2q_H^2-(\Delta P)^2\right]<\left(\frac{1+\alpha}{1+\gamma}\right)^2q_H=\Pi_H^*,$$

where $\Delta P=\widehat{P}_H-P_H^*$. Then we have $\frac{d\widehat{\Pi}_H}{dr}=\frac{2}{q_H}\left[\left(\frac{1+\alpha}{1+\gamma}\right)q_H^2\frac{d}{dr}\left(\frac{1+\alpha}{1+\gamma}\right)-\Delta P\frac{d(\Delta P)}{dr}\right]$, and

$$\left.\frac{d\widehat{\Pi}_H}{dr}\right|_{r=0}=-\frac{2}{q_H}\Delta P\frac{d(\Delta P)}{dr}>0,\ \text{ and }\ \left.\frac{d\widehat{\Pi}_H}{dr}\right|_{r=\widehat{r}}=-\frac{\delta\widehat{r}(1+\alpha)(1-\gamma)^2q_H}{2(1-\widehat{r})^2\gamma(1+\gamma)(1-\delta+\gamma)^2}<0.$$

By continuity of $\frac{d\widehat{\Pi}_H}{dr}$ in r, there must exist a threshold r^* such that $\frac{d\widehat{\Pi}_H}{dr}\big|_{r=r^*}=0$. To complete the proof, we only need to establish the uniqueness of the threshold r^*.

First, notice that $\frac{d\widehat{\Pi}_H}{dr}$ is a function of $\alpha(\delta,r)$ and $\gamma(\delta,r)$. Given $\gamma(\delta,r)=\sqrt{1-(1-r)\delta}\in[\sqrt{1-\delta},1]$, we can rewrite $\alpha(\delta,r)=\alpha(\delta,\gamma)=-\frac{1-\delta-\gamma^2}{2(1-\delta+\gamma)}$ and substitute it into $\frac{d\widehat{\Pi}_H}{dr}$. Then we have $\frac{d\widehat{\Pi}_H}{dr}=\frac{d\widehat{\Pi}_H}{d\gamma}\times\frac{d\gamma}{dr}$ and $\frac{d\gamma}{dr}\neq 0$, which implies that we can instead show that $\frac{d\widehat{\Pi}_H}{d\gamma}$ has a unique root for $\sqrt{1-\delta}\leq\gamma\leq 1$. We have

$$\frac{d\widehat{\Pi}_H}{d\gamma}\propto\left(\frac{1+\alpha(\delta,\gamma)}{1+\gamma}\right)q_H^2\frac{d}{d\gamma}\left(\frac{1+\alpha(\delta,\gamma)}{1+\gamma}\right)-\Delta P\frac{d\Delta P}{d\gamma}=\frac{G_1+G_2}{4(1+\gamma)^2(1+\gamma-\delta)^3}$$

where G_1 and G_2 are functions of γ, δ, q_H, and q_L as follows:

$$\begin{aligned}G_1=&[-(2+\delta)\gamma^4+\delta^2\gamma^3+12(1-\delta)\gamma^2+(\delta^3+11\delta^2-28\delta+16)\gamma+3(2-\delta)(1-\delta)^2]q_H^2\\&+[(6-\delta)\gamma^4+(-\delta^2-8\delta+8)\gamma^3-12(1-\delta)\gamma^2+(-\delta^3-19\delta^2+44\delta-24)\gamma-5(2-\delta)(1-\delta)^2]q_Hq_L\\&+[-(4-\delta)\gamma^2-(8-6\delta)\gamma^3+(6\delta^2-14\delta+8)\gamma+(-\delta^3+6\delta^2-9\delta+4)]q_L^2,\\G_2=&-(q_H-q_L)(1+\gamma-\delta)(1+\gamma)[2(1+\gamma)^2-(1+\gamma)(3+\gamma)\delta+\delta^2]M\\&-\frac{1}{(1+\gamma)(1+\gamma-\delta)M}\times\{(1+\gamma-\delta)[2(1-\delta)+(2-\delta)\gamma](q_H-q_L)^2\\&\{2(1-\gamma)(1+\gamma-\delta)^2q_H+[(4-\delta)\gamma^2+4(1-\delta)\gamma-\delta(1-\delta)](1+\gamma)q_L\}\},\end{aligned}$$

where $M=\sqrt{\left(\frac{1-\gamma}{1+\gamma}\right)^2(q_H-q_L)^2+2\left(\frac{1}{1+\gamma}+\frac{\gamma}{1+\gamma-\delta}\right)\left(\frac{1-\gamma}{1+\gamma}\right)(q_H-q_L)q_L}$.

Then, it suffices to show $\frac{d(G_1+G_2)}{d\gamma} < 0$. We have

$$\frac{dG_2}{d\gamma} = \frac{(q_H - q_L)^3 G_3(q_H)}{(1+\gamma)^3(1+\gamma-\delta)^2 M^3}, \text{and } \; G_3(q_H) = b_1 q_H^2 + b_2 q_H + b_3,$$

where the coefficients b_1, b_2, and b_3 are functions of γ, δ, and q_L. Since $G_3'''(q_H) < 0$ and $G_3'(q_L) < 0$, we have $G_3(q_H) < G_3(q_L) < 0$, which implies that $\frac{dG_2}{d\gamma} < 0$. For $\frac{dG_1}{d\gamma}$, we consider two cases. If $\frac{dG_1}{d\gamma} \leq 0$, then we have $\frac{d(G_1+G_2)}{d\gamma} < 0$; otherwise, if $\frac{dG_1}{d\gamma} > 0$, then, we have

$$\begin{aligned}
\frac{d(G_1+G_2)}{d\gamma} \propto & \frac{dG_1}{d\gamma} M + \frac{(q_H - q_L)^3 G_3}{(1+\gamma)^3(1+\gamma-\delta)^2 M^2} \\
< & \frac{dG_1}{d\gamma} \frac{1-\sqrt{1-\delta}}{1+\sqrt{1-\delta}}(q_H + q_L) + \frac{(q_H - q_L)^3 G_3}{(1+\gamma)^3(1+\gamma-\delta)^2 M^2} \\
\propto & F(\rho)
\end{aligned}$$

where the " $<$ " is due to $M < \frac{1-\sqrt{1-\delta}}{1+\sqrt{1-\delta}}(q_H + q_L)$ and

$$F(\rho) = c_1\rho^4 + c_2\rho^3 + c_3\rho^2 + c_4\rho + c_5,$$

where c_1, c_2, c_3, c_4, and c_5 are functions of γ and δ, and $\rho = \frac{q_H}{q_L} \in [1, 1/\sqrt{1-\delta}]$.

Lastly, we prove $F(\rho) < 0$ for $1 < \rho < 1/\sqrt{1-\delta}$. Note that $H(\rho) = c_1\rho^3 + c_2\rho^2 + c_3\rho + c_4$ can be bounded by two linear functions of ρ. Specifically, $H''(\rho) = 6c_1\rho + 2c_2$ is a linear function of ρ. For $\rho \in (1, 1/\sqrt{1-\delta})$, since $H''(1) > 0$ and $H''(1/\sqrt{1-\delta}) < 0$ can not hold at the same time, $H''(\rho)$ can only be (i) always positive, (ii) always negative, or (iii) first negative and then positive. This implies that $H'(\rho) = 3c_1\rho^2 + 2c_2\rho + c_3$ only (i) increases with ρ, (ii) decreases with ρ, or (iii) first decreases and then increases with ρ. Then, the $H'(\rho)$ achieves the maximum at either $\rho = 1$ or $\rho = 1/\sqrt{1-\delta}$. Since $H'(1) < 0$ and $H'(1/\sqrt{1-\delta}) < 0$, $H'(\rho)$ is always negative and H is always decreasing in ρ for $1 < \rho < 1/\sqrt{1-\delta}$.

For $\rho \in (1, 1/\sqrt{1-\delta})$, $H(\rho)$ can be (i) convex; (ii) concave, (iii) and first concave and then convex. For (i), $H(\rho)$ can be bounded by the straight line that connects $H(1)$ and $H(1/\sqrt{1-\delta})$, which is $H_1(\rho) = H(1) + \frac{\sqrt{1-\delta}}{1-\sqrt{1-\delta}}\left(H\left(\frac{1}{\sqrt{1-\delta}}\right) - H(1)\right)(\rho - 1)$. For (ii) and (iii), $H(\rho)$ can be bounded by the tangent line passing through $(1, H(1))$, which is $H_2(\rho) = H(1) + H'(1)(\rho - 1)$. Then, we have $H(\rho) < \max\{H_1(\rho), H_2(\rho)\}$, and

$$F(\rho) = \rho H(\rho) + c_5 < \rho \max\{H_1(\rho), H_2(\rho)\} + c_5 = \max\left\{\rho H_1(\rho) + c_5, \rho H_2(\rho) + c_5\right\}.$$

The rest is to show $F_1(\rho) = \rho H_1(\rho) + c_5 < 0$ and $F_2(\rho) = \rho H_2(\rho) + c_5 < 0$, which are quadratic functions of ρ. If $H(1/\sqrt{1-\delta}) \leq (2 - 1/\sqrt{1-\delta})H(1)$, then $F_1(\rho)$ is decreasing in ρ for $1 < \rho < 1/\sqrt{1-\delta}$ and thus $F_1(\rho) \leq F_1(1) = M(1) + c_5 < 0$; otherwise, if $H(1/\sqrt{1-\delta}) > (2 - 1/\sqrt{1-\delta})H(1)$, we have $F_1(\rho) \leq \frac{\sqrt{1-\delta}}{1-\sqrt{1-\delta}}\left[-\frac{\left(\frac{H(1)}{\sqrt{1-\delta}} - H\left(\frac{1}{\sqrt{1-\delta}}\right)\right)^2}{4\left(H\left(\frac{1}{\sqrt{1-\delta}}\right) - H(1)\right)} + \frac{1-\sqrt{1-\delta}}{\sqrt{1-\delta}}c_5\right] < 0$. We have $F_2(\rho) \leq -\frac{[H(1)-H'(1)]^2}{4H'(1)} + c_5 < 0$. $\square$

Proof of Proposition 6: Effect of Royalties on Social Welfare

Proof. We show that $\widehat{D}_H$ can increase with r in a non-empty interval. We have

$$\left.\frac{d\widehat{D}_H}{dr}\right|_{r=0} = \left\{ \frac{(1-\sqrt{1-\delta})q_H + (1+\sqrt{1-\delta})q_L}{\sqrt{[(1-\sqrt{1-\delta})q_H + (1+\sqrt{1-\delta})q_L]^2 - 4q_L^2}} - 1 \right\} \frac{\delta(q_H - q_L)}{2(1+\sqrt{1-\delta})^2\sqrt{1-\delta}q_H} > 0.$$

By continuity of $d\widehat{D}_H/dr$ in r, there must exist a non-empty interval $0 \leq r < r'$ such that $\frac{d\widehat{D}_H}{dr} > 0$. Part (ii) and (iii) are due to $dD_j^*/dr < 0$ and $dd_j^*/dr < 0$, as shown in the proof of Proposition 1. □

Online Appendix for *From Canvas to Blockchain: Impact of Royalties on Art Market Efficiency*

Proof of Proposition 7: Royalty Rate Chosen by the Artist, Incomplete Information

Proof. In this proof, we introduce $\Pi_{jr}(P, r; \mu)$ to denote the j-type artist's profit when she chooses price P and royalty rate r, and the buyer 0's belief is μ.

First, we show that under incomplete information with the royalty rate chosen by the artist, there does not exist a pooling equilibrium that survives the intuitive criterion.

This can be proved by contradiction. Suppose a pooling equilibrium equilibrium exists with strategy $(\widetilde{P}, \widetilde{r})$. Following the same logic in the proof of Lemma A1, we can directly have an off-equilibrium-path strategy $(\widetilde{P}', \widetilde{r})$ that can fail the intuitive criterion, where $\widetilde{P}'$ is equal to P' in the proof of Lemma A1 with $r = \widetilde{r}$.

Second, we prove the existence and uniqueness of the separating equilibrium in three steps.

Step 1: We prove that the equilibrium strategies constitute a PBE.

Under complete information, the artist chooses $r_j^* = 0$ and $P_j^*|_{r=0} = \frac{q_j}{1+\sqrt{1-\delta}}$ for $j \in \{H, L\}$. If the optimal strategy under complete information can constitute a separating equilibrium, we have

$$\Pi_{Lr}(P_H^*|_{r=0}, 0; 1) \leq \Pi_{Lr}(P_L^*|_{r=0}, 0; 0) \equiv \Pi_{Lr}^* \Leftrightarrow \frac{q_H}{q_L} \geq k(\delta, 0) = \frac{1}{\sqrt{1-\delta}}.$$

Otherwise, if $\frac{q_H}{q_L} < \frac{1}{\sqrt{1-\delta}}$, we must have $\Pi_{Lr}(P_H, r_H; 1) \leq \Pi_{Lr}^*$.

Suppose the high-type artist chooses $0 \leq r \leq 1$. There exists a threshold $\overline{r} \in (0, 1)$ such that:

(a) for $0 \leq r < \overline{r}$, the high-type artist's optimal price under exogenous royalty rate, P_H^*, cannot achieve separation, that is $\Pi_{Lr}(P_H^*, r; 0) > \Pi_{Lr}^*$. So the high-type artist's price must satisfy $\Pi_{Lr}(P_H, r; 1) \leq \Pi_{Lr}^*$, which is equivalent to

$$P_H \geq \widehat{P}_{Hr}(r) = \frac{\delta(1-r)\pi_H^* + (1-R)q_L + \sqrt{[(1+R)q_L + \delta(1-r)\pi_H^*]^2 - 4\Pi_{Lr}^* q_L}}{2}$$
$$\text{or } P_H \leq \widehat{P}''_{Hr}(r) = \frac{\delta(1-r)\pi_H^* + (1-R)q_L - \sqrt{[(1+R)q_L + \delta(1-r)\pi_H^*]^2 - 4\Pi_{Lr}^* q_L}}{2}.$$

(b) For $\overline{r} \leq r \leq 1$, the high-type artist's optimal price under exogenous royalty rate, P_H^*, can achieve separation, that is $\Pi_{Lr}(P_H^*, r; 0) \leq \Pi_{Lr}^*$. In this case, the high-type artist's profit $\Pi_{Hr}(P_H^*, r; 1)$ decreases with r. In summary, there exists a unique strategy $(\widehat{P}_{Hr}(\widehat{r}_H), \widehat{r}_H)$ that can maximize the high-type artist's profit and prevent the low-type artist from mimicking, where $\widehat{r}_H = \arg\max_r \widehat{\Pi}_{Hr}(\widehat{P}_{Hr}(r), r; 1) \in [0, \overline{r})$.[OA1] We have $\widehat{r}_H > 0$ since $d\widehat{\Pi}_{Hr}(\widehat{P}_{Hr}(r), r; 1)/dr\big|_{r=0} > 0$.

We show that for any off-equilibrium-path strategy, two types of artists cannot make a profitable deviation under the specified off-equilibrium-path belief. The low-type artist

[OA1]The parameter range that allows $f(r) = \Pi_{Hr}(\widehat{P}_{Hr}(r), r; 1)$ to have multiple identical peaks has zero measure on the entire parameter space.

adopts the optimal strategy under belief $\mu = 0$ and thus does not deviate. For the high-type artist, if $\frac{q_H}{q_L} \geq \frac{1}{\sqrt{1-\delta}}$, the high-type's strategy is the optimal one under complete information and thus does not deviate. If $\frac{q_H}{q_L} < \frac{1}{\sqrt{1-\delta}}$, we can show that $\widehat{\Pi}_{Hr}(\widehat{P}_{Hr}(\widehat{r}_H), \widehat{r}_H; 1) \geq \max_{P_H, r} \Pi_{Hr}(P_H, r; 0)$. Let us consider two cases. For $0 \leq r < \overline{r}$, due to $\widehat{P}_{Hr}(r) \leq \widehat{P}_H$, we have

$$\widehat{\Pi}_{Hr}(\widehat{P}_{Hr}(r), r; 1) \geq \widehat{\Pi}_H(\widehat{P}_H; 1) \geq \max_{P_H} \Pi_H(P_H; 0),$$

where the second "$\geq$" is shown in the proof of Proposition 3. This easily implies that

$$\widehat{\Pi}_{Hr}(\widehat{P}_{Hr}(\widehat{r}_H), \widehat{r}_H; 1) \geq \max_{r \in [0, \overline{r})} \widehat{\Pi}_{Hr}(\widehat{P}_{Hr}(r), r; 1) \geq \max_{P_H, r \in [0, \overline{r})} \Pi_{Hr}(P_H, r; 0).$$

For $\overline{r} \leq r \leq 1$, we have

$$\widehat{\Pi}_{Hr}(\widehat{P}_{Hr}(\widehat{r}_H), \widehat{r}_H; 1) \geq \max_{r \in [\overline{r}, 1]} \Pi_{Hr}(P_H^*, r; 1) \geq \max_{P_H, r \in [\overline{r}, 1]} \Pi_{Hr}(P_H, r; 0).$$

Step 2: We prove the uniqueness of the equilibrium by contradiction.

Suppose there exists another separating equilibrium with $\{P_H, r_H, P_L, r_L\}$ that survives the intuitive criterion.

If $\frac{q_H}{q_L} \geq \frac{1}{\sqrt{1-\delta}}$, for any high-type strategy $(P_H, r_H) \neq (P_H^*\big|_{r=0}, 0)$, the low-type artist cannot make a profitable deviation to $(P_H^*\big|_{r=0}, 0)$, but the high-type artist can benefit from deviating to $(P_H^*\big|_{r=0}, 0)$ under the only reasonable belief $\mu = 1$ in light of intuitive criterion.

If $\frac{q_H}{q_L} < \frac{1}{\sqrt{1-\delta}}$, we consider an off-equilibrium-path strategy $(\widehat{P}_{Hr}(\widehat{r}_H) + \epsilon, \widehat{r}_H)$. The low-type artist cannot make any profitable deviation, while the high-type artist can benefit by deviating to this strategy under $\mu = 1$. Thus, such equilibrium fails the intuitive criterion.

Step 3: We show that the specified belief survives the intuitive criterion.

Following the same logic in the proof of Proposition 3, we only need to show that for any off-equilibrium-path strategy (P', r'), the low-type artist is willing to deviate under the most optimistic belief $\mu = 1$, or the high-type artist cannot make a profitable deviation even if it is perceived as the high-type.

If $\frac{q_H}{q_L} \geq \frac{1}{\sqrt{1-\delta}}$, the high-type artist sets the optimal strategy under complete information and thus does not want to deviate under any belief, so we can specify $\mu(P', r') = 0$ for any off-equilibrium-path strategy (P', r').

If $\frac{q_H}{q_L} < \frac{1}{\sqrt{1-\delta}}$. First, we consider off-equilibrium-path strategy (P', r') with $0 \leq r < \overline{r}$. If $P' < \widehat{P}_{Hr}(r)$, the low-type artist can make profitable deviation under the most optimistic belief. If $P' > \widehat{P}_{Hr}(r)$, the high-type artist cannot make any profitable deviation under any beliefs, and the low-type artist doesn't deviate even under $\mu = 1$, so we can specify belief as $\mu = 0$ for convenience. Second, we consider off-equilibrium-path strategy (P', r') with $\overline{r} \leq r \leq 1$, we have $\widehat{\Pi}_{Hr}(\widehat{P}_{Hr}(\widehat{r}_H), \widehat{r}_H; 1) \geq \max_{r \in [\overline{r}, 1]} \Pi_{Hr}(r, P_H^*; 1)$ and thus the high-type artist does not want to deviate under any belief. □

Proof of Proposition 8: Infinite Resale Opportunities, Complete Information

Proof. We first consider the resale market $t \geq 1$.

Seller t sets the price p_{jt} to maximize the expected resale payoff $(1-r)\pi_{j,t}$. Buyer t purchases if and only if $\theta_t q_j - p_{jt} + \delta(1-r)\pi_{j,t+1} \geq 0$. Therefore, the transaction probability is

$$d_{jt}(p_{jt}) = \Pr\left(\theta_t \geq \frac{p_{jt} - \delta(1-r)\pi_{j,t+1}}{q_j}\right) = 1 - \frac{p_{jt} - \delta(1-r)\pi_{j,t+1}}{q_j}.$$

Note that if buyer t does not purchase, seller t can sell the artwork at $t+1$ with expected resale payoff $\pi_{j,t+1}$. Therefore, the optimal price is:

$$p_{jt}^* = \arg\max_{p_{jt}}(1-r)\pi_{jt} = \arg\max_{p_{jt}}(1-r)\left[p_{jt}d_{jt}(p_{jt}) + (1-d_{jt}(p_{jt}))\,\delta\pi_{j,t+1}\right] = \frac{1}{2}\left(q_j + (2-r)\delta\pi_{j,t+1}\right).$$

Seller t's expected resale profit under the optimal price is

$$\pi_{jt}^* = p_{jt}^* d_{jt}(p_{jt}^*) + (1-d_{jt}(p_{jt}^*))\delta\pi_{j,t+1} = \frac{q_j^2 + 2(2-r)\delta q_j \pi_{j,t+1} + (\delta r \pi_{j,t+1})^2}{4q_j}.$$

Because of the time stationarity of all resale markets, we have $\pi_{jt}^* = \pi_{j,t+1} = \pi_{jI}^*$ in equilibrium. Then we can solve for π_{jI}^*, as well as p_{jI}^* and d_{jI}^* in resale markets, where the subscript "I" stands for "infinite resale opportunities".

Now we consider the primary market $t=0$. The artist sets price P_j to maximize her expected profit:

$$\begin{aligned}\Pi_{jI}^* &= \max_{P_j}\left(P_j + \delta r \sum_{t=0}^{\infty}\delta^t\left(p_{jI}^* d_{jI}^*\right)\right)\Pr\left(u_{0j} \geq 0\right) = \max_{P_j}\left(P_j + \delta r \frac{p_{jI}^* d_{jI}^*}{1-\delta}\right)\left(1 - \frac{P_j - \delta(1-r)\pi_{jI}^*}{q_j}\right)\\ &= \max_{P_j}\left(P_j + R_I q_j\right)\left(1 - \frac{P_j - \delta(1-r)\pi_{jI}^*}{q_j}\right).\end{aligned}$$

There are two possible cases:

- Case (a): If $(1-R_I)q_j - \delta(1-r)\pi_{jI}^* > 0$, which is equivalent to $0 < \delta < \frac{4}{5}$, or $\frac{4}{5} \leq \delta < 2(\sqrt{2}-1)$ and $\frac{\sqrt{5\delta-4}(3\delta-2+\sqrt{\delta(5\delta-4)})}{2\sqrt{\delta}(1-\delta)} < r < 1$, the optimal price is interior and can be solved by the first order condition: $P_{jIa}^* = \frac{(1-R_I)q_j + \delta(1-r)\pi_{jI}^*}{2}$.
- Case (b): If $(1-R_I)q_j - \delta(1-r)\pi_{jI}^* \leq 0$, which is equivalent to $\frac{4}{5} \leq \delta < 2(\sqrt{2}-1)$ and $0 \leq r \leq \frac{\sqrt{5\delta-4}(3\delta-2+\sqrt{\delta(5\delta-4)})}{2\sqrt{\delta}(1-\delta)}$, or if $2(\sqrt{2}-1) \leq \delta < 1$, the optimal price is a corner solution: $P_{jIb}^* = \delta(1-r)\pi_j^*$.

The equilibrium transaction probabilities in the primary market and the artist's profits in the above two cases can be solved as well.

Comparative statics: For resale markets:

$$\frac{dp_{jI}^*}{dr} = -\frac{\left(\delta(1+\delta) + \delta\sqrt{(1-\delta)(1-(1-r)\delta)}\right)q_j}{2\sqrt{1-(1-r)\delta}\left(\sqrt{1-\delta} + \sqrt{1-(1-r)\delta}\right)^3} < 0$$

$$\frac{dd_{jI}^*}{dr} = -\frac{\delta\sqrt{1-\delta}}{2\sqrt{1-(1-r)\delta}\left(\sqrt{1-\delta} + \sqrt{1-(1-r)\delta}\right)^2} < 0$$

$$\frac{d\pi^*_{jI}}{dr} = -\frac{\delta q_j}{\sqrt{1-(1-r)\delta}\left(\sqrt{1-\delta}+\sqrt{1-(1-r)\delta}\right)^3} < 0$$

For the primary market, there are two cases.

Case (a): When $0 < \delta < 4/5$, or when $4/5 \leq \delta < 2(\sqrt{2}-1)$ and $\frac{\sqrt{5\delta-4}(3\delta-2+\sqrt{\delta(5\delta-4)})}{2\sqrt{\delta}(1-\delta)} < r < 1$, we have

$$\begin{aligned}
\frac{dP^*_{jIa}}{dr} &= -\frac{4(2-\delta)\sqrt{(1-\delta)(1-(1-r)\delta)}+8-4(3-r)\delta+(4-5r)\delta^2}{4\sqrt{(1-\delta)(1-(1-r)\delta)}\left(\sqrt{1-\delta}+\sqrt{1-(1-r)\delta}\right)^4}\delta q_j < 0 \\
\frac{dD^*_{jIa}}{dr} &= -\frac{r\delta^3}{4\sqrt{(1-\delta)(1-(1-r)\delta)}\left(\sqrt{1-\delta}+\sqrt{1-(1-r)\delta}\right)^4} < 0 \\
\frac{d\Pi^*_{jIa}}{dr} &= -\frac{r\delta^3((1+R_I)q_j+\delta(1-r)\pi^*_{jI})}{4\sqrt{(1-\delta)(1-(1-r)\delta)}\left(\sqrt{1-\delta}+\sqrt{1-(1-r)\delta}\right)^4} < 0
\end{aligned}$$

Case (b): When $4/5 \leq \delta < 2(\sqrt{2}-1)$ and $0 \leq r \leq \frac{\sqrt{5\delta-4}(3\delta-2+\sqrt{\delta(5\delta-4)})}{2\sqrt{\delta}(1-\delta)}$, or if $2(\sqrt{2}-1) \leq \delta < 1$, we have

$$\begin{aligned}
\frac{dP^*_{jIb}}{dr} &= -\frac{\left(\delta+\delta\sqrt{(1-\delta)(1-(1-r)\delta)}\right)q_j}{\sqrt{1-(1-r)\delta}\left(\sqrt{1-\delta}+\sqrt{1-(1-r)\delta}\right)^3} < 0 \\
\frac{dD^*_{jIb}}{dr} &= 0 \\
\frac{d\Pi^*_{jIb}}{dr} &= -\frac{r\delta^3 q_j}{2\sqrt{(1-\delta)(1-(1-r)\delta)}\left(\sqrt{1-\delta}+\sqrt{1-(1-r)\delta}\right)^4} < 0
\end{aligned}$$

□

Proof of Proposition 9: Infinite Resale Opportunities, Incomplete Information

Proof. First, we prove that there does not exist a pooling equilibrium that survives the intuitive criterion.

This proof largely follows the proof of Lemma A1, and therefore we mainly highlight the differences.

Denote $\overline{\pi}_I(\mu) = \mu\pi^*_{HI} + (1-\mu)\pi^*_{LI}$. The artist j's profit under belief μ is $\Pi_j(P;\mu) = (P + R_I q_j)D_j(P;\mu)$, where

$$D_L(P;\lambda) = \begin{cases} 1 & 0 \leq P < \delta(1-r)\overline{\pi}_I(\overline{\lambda}) \\ 1 - \frac{P-\delta(1-r)\overline{\pi}_I(\overline{\lambda})}{q_L} & \text{if} \quad \delta(1-r)\overline{\pi}_I(\overline{\lambda}) \leq P < \delta(1-r)\overline{\pi}_I(\overline{\lambda}) + q_L \\ 0 & \text{otherwise} \end{cases},$$

and

$$D_H(P;\lambda) = \begin{cases} 1 & 0 \le P < \delta(1-r)\overline{\pi}_I(\overline{\lambda}) \\ 1 - \frac{P-\delta(1-r)\overline{\pi}_I(\overline{\lambda})}{q_H} & \text{if } \delta(1-r)\overline{\pi}_I(\overline{\lambda}) \le P < \delta(1-r)\overline{\pi}_I(\overline{\lambda}) + q_L \\ 1 - \frac{q_L}{q_H} & \text{if } \delta(1-r)\overline{\pi}_I(\overline{\lambda}) + q_L \le P < \delta(1-r)\pi^*_{HI} + q_L \\ 1 - \frac{P-\delta(1-r)\pi^*_{HI}}{q_H} & \text{if } \delta(1-r)\pi^*_{HI} + q_L \le P \le \delta(1-r)\pi^*_{HI} + q_H \\ 0 & \text{otherwise.} \end{cases} \tag{OA1}$$

Suppose there exists a pooling equilibrium with price $\widetilde{P} < \delta(1-r)\overline{\pi}_I(\overline{\lambda}) + q_L$; otherwise, the low-type artist has zero profit and thus will deviate. There are two cases.
(i) If $0 \le \widetilde{P} < \delta(1-r)\overline{\pi}_I(\overline{\lambda})$, then the two types of artists' profits are

$$\Pi_L(\widetilde{P};\lambda) = \widetilde{P} + R_I q_L, \text{and } \Pi_H(\widetilde{P};\lambda) = \widetilde{P} + R_I q_H.$$

We consider an off-equilibrium-path price $P_o > \delta(1-r)\pi^*_{HI} > \widetilde{P}$ such that $\Pi_L(P_o;1) = \Pi_L(\widetilde{P};\lambda)$, then we have

$$\Pi_H(P_o,1) - \Pi_H(\widetilde{P},\lambda) = \frac{q_H - q_L}{q_H q_L} P_o \left[P_o - \delta(1-r)\pi^*_{HI}\right] > 0.$$

Therefore, $P' = P_o + \epsilon$ with sufficiently small $\epsilon > 0$ satisfies $\Pi_L(P';1) < \Pi_L(\widetilde{P};\lambda)$ and $\Pi_H(P';1) > \Pi_H(\widetilde{P};\lambda)$, which violates the intuitive criterion.
(ii) If $\delta(1-r)\overline{\pi}_I(\overline{\lambda}) \le \widetilde{P} < \delta(1-r)\overline{\pi}_I(\overline{\lambda}) + q_L$, then the two types of artists' profits are

$$\Pi_L(\widetilde{P};\lambda) = \left(\widetilde{P} + R_I q_L\right)\left(1 - \frac{\widetilde{P} - \delta(1-r)\overline{\pi}_I(\overline{\lambda})}{q_L}\right)$$
$$\text{and } \Pi_H(\widetilde{P};\lambda) = \left(\widetilde{P} + R_I q_H\right)\left(1 - \frac{\widetilde{P} - \delta(1-r)\overline{\pi}_I(\overline{\lambda})}{q_H}\right).$$

We consider an off-equilibrium-path price $P_o > \widetilde{P}$ such that $\Pi_L(P_o;1) = \Pi_L(\widetilde{P};\lambda)$, then we have

$$\begin{aligned}\Pi_H(P_o,1) - \Pi_H(\widetilde{P},\lambda) =& (\Pi_H(P_o,1) - \Pi_L(P_o,1)) - (\Pi_H(\widetilde{P},\lambda) - \Pi_L(\widetilde{P},\lambda)) \\ =& \frac{q_H - q_L}{q_H}\left[(P_o - \widetilde{P})(1-R_I) + R_I\delta(1-r)(\overline{\pi}_I(1) - \overline{\pi}_I(\overline{\lambda}))\right] > 0.\end{aligned}$$

Therefore, $P' = P_o + \epsilon$ with sufficiently small $\epsilon > 0$ satisfies $\Pi_L(P';1) < \Pi_L(\widetilde{P};\lambda)$ and $\Pi_H(P';1) > \Pi_H(\widetilde{P};\lambda)$, which violates the intuitive criterion.

In summary, there does not exist any pooling equilibrium under the intuitive criterion.

Then, we solve for the separating equilibrium under incomplete information.

To begin with, we show that the equilibrium can constitute a PBE in two cases.
(i) $0 < \delta < 4/5$, or $4/5 \le \delta < 2(\sqrt{2}-1)$ and $\frac{\sqrt{5\delta-4}(3\delta-2+\sqrt{\delta(5\delta-4)})}{2\sqrt{\delta}(1-\delta)} < r < 1$

First, there exists a threshold of $\frac{q_H}{q_L}$ such that the optimal price under complete information can constitute a separating equilibrium if and only if

$$\Pi_L(P^*_{HIa};1) \leq \Pi_L(P^*_{LIa};0) \Leftrightarrow \frac{q_H}{q_L} \geq k_I(\delta, r),$$

where k_I is a function of δ and r. Otherwise, if $q_H/q_L < k_I(\delta, r)$, we must have $\Pi_L(P_H;1) \leq \Pi_L(P^*_L;0)$, which is equivalent to

$$\begin{aligned} P_H \geq \widehat{P}_{HIa} &= \frac{\delta(1-r)\pi^*_{HI} + (1-R_I)q_L + \sqrt{[(1+R_I)q_L + \delta(1-r)\pi^*_{HI}]^2 - 4\Pi^*_{LIa}q_L}}{2} \\ \text{or } P_H \leq \widehat{P}''_{HIa} &= \frac{\delta(1-r)\pi^*_{HI} + (1-R_I)q_L - \sqrt{[(1+R_I)q_L + \delta(1-r)\pi^*_{HI}]^2 - 4\Pi^*_{LIa}q_L}}{2}, \end{aligned}$$

where $\widehat{P}_{HIa} > P^*_{HIa}$.

Then we show that for any off-equilibrium-path price, the high-type artist cannot make a profitable deviation under the specified off-equilibrium-path belief. If $\frac{q_H}{q_L} \geq k_I(\delta, r)$, the equilibrium price is the optimal one under complete information, and thus high-type artist does not deviate. If $\frac{q_H}{q_L} < k_I(\delta, r)$, we can show that $\Pi_H(\widehat{P}_{HIa};1) \geq \max_{P_H} \Pi_H(P_H;0)$. Following the transaction probability in equation (OA1), the high-type artist's profit under belief $\lambda = 0$ is

$$\Pi_H(P_H;0) = \begin{cases} (P_H + R_I q_H) & \text{if } 0 \leq P_H < \delta(1-r)\pi^*_{LI} \\ (P_H + R_I q_H)\left(1 - \frac{P_H - \delta(1-r)\pi^*_{LI}}{q_H}\right) & \text{if } \delta(1-r)\pi^*_{LI} \leq P_H < \delta(1-r)\pi^*_{LI} + q_L, \\ (P_H + R_I q_H)\left(1 - \frac{q_L}{q_H}\right) & \text{if } \delta(1-r)\pi^*_{LI} + q_L \leq P_H < \delta(1-r)\pi^*_{HI} + q_L, \\ (P_H + R_I q_H)\left(1 - \frac{P_H - \delta(1-r)\pi^*_{H}}{q_H}\right) & \text{if } \delta(1-r)\pi^*_{HI} + q_L \leq P_H \leq \delta(1-r)\pi^*_{HI} + q_H. \end{cases}$$

For $\delta(1-r)\pi^*_{HI} + q_L \leq P_H \leq \delta(1-r)\pi^*_{HI} + q_H$, we have

$$\frac{d\Pi_H(P_H;0)}{dP_H} = \frac{2}{q_H}\left(\frac{(1-R_I)q_H}{2} + \frac{\delta(1-r)\pi^*_{HI}}{2} - P_H\right) \leq \frac{2}{q_H}\left(\frac{(1-R_I)q_H}{2} - \frac{\delta(1-r)\pi^*_{HI}}{2} - q_L\right) < 0,$$

where the "$\leq$" is obtained due to $P_H \geq \delta(1-r)\pi^*_{HI} + q_L$. This means that $\delta(1-r)\pi^*_{HI} + q_L$ is the unique local maximizer of $\Pi_H(P_H;0)$ for $P_H \geq \delta(1-r)\pi^*_{LI} + q_L$. We also have $\widehat{P}_{HIa} < \delta(1-r)\pi^*_{HI} + q_L$. Given the quadratic form of $\Pi_H(P_H, 1)$ and $\Pi_H(\delta(1-r)\pi^*_{HI} + q_L; 0) = \Pi_{HI}(\delta(1-r)\pi^*_H + q_L; 1)$, we have

$$\Pi_H(\widehat{P}_{HIa};1) \geq \Pi_H(\delta(1-r)\pi^*_{HI} + q_L;1) = \Pi_H(\delta(1-r)\pi^*_{HI} + q_L;0).$$

For $0 \leq P_H < \delta(1-r)\pi^*_{LI} + q_L$, we have $\Pi_H(P_H;0) \leq \frac{1}{4q_H}\left[q_H + \delta(1-r)\pi^*_{LI} + Rq_H\right]^2$ due to its quadratic form. It suffices to have

$$\Pi_H(\widehat{P}_{HIa};1) - \frac{1}{4q_H}\left(q_H + \delta(1-r)\pi^*_{LI} + R_I q_H\right)^2 > 0.$$

(ii) $4/5 \leq \delta < 2(\sqrt{2}-1)$ and $0 \leq r < \frac{\sqrt{5\delta-4}(3\delta-2+\sqrt{\delta(5\delta-4)})}{2\sqrt{2}(1-\delta)}$, or $2(\sqrt{2}-1) \leq \delta < 1$

First, the optimal prices under complete information cannot achieve separation since

$$\Pi_L(P^*_{HIb};1)-\Pi_L(P^*_{LIb};0)=\delta(1-r)(\pi^*_{HI}-\pi^*_{LI})>0.$$

Therefore, we must have $\Pi_L(P_H;1)\leq\Pi_L(P^*_{LIb};0)$, which is equivalent to

$$\begin{aligned} P_H \geq \widehat{P}_{HIb} &= \frac{\delta(1-r)\pi^*_{HI}+(1-R_I)q_L+\sqrt{[(1+R_I)q_L+\delta(1-r)\pi^*_{HI}]^2-4\Pi^*_{LIb}q_L}}{2} \\ \text{or } P_H \leq \widehat{P}''_{HIb} &= \frac{\delta(1-r)\pi^*_{HI}+(1-R_I)q_L-\sqrt{[(1+R_I)q_L+\delta(1-r)\pi^*_{HI}]^2-4\Pi^*_{LIb}q_L}}{2}, \end{aligned}$$

where $\widehat{P}_{HIb}>P^*_{HIb}$.

Then we show that for any off-equilibrium-path price, the high-type artist cannot make a profitable deviation under the specified off-equilibrium-path belief, that is $\Pi_H(\widehat{P}_{HIb};1)\geq\max_{P_H}\Pi_H(P_H;0)$.

For $P_H\geq\delta(1-r)\pi^*_{LI}+q_L$, $\delta(1-r)\pi^*_{HI}+q_L$ is the unique local maximizer of $\Pi_H(P_H;0)$ as shown in (i). Similarly, because of $\widehat{P}_{HIb}<\delta(1-r)\pi^*_{HI}+q_L$, we have

$$\Pi_H(\widehat{P}_{HIb};1)\geq\Pi_H(\delta(1-r)\pi^*_{HI}+q_L;1)=\Pi_H(\delta(1-r)\pi^*_{HI}+q_L;0).$$

For $0\leq P_H<\delta(1-r)\pi^*_{LI}+q_L$, let us consider two cases. If $(1-R_I)q_H-\delta(1-r)\pi^*_{LI}\geq 0$, we have $\Pi_H(P_H;0)\leq\frac{1}{4q_H}\left[q_H+\delta(1-r)\pi^*_{LI}+R_Iq_H\right]^2$. It suffices to have

$$\Pi_H(\widehat{P}_H;1)-\frac{1}{4q_H}\left[q_H+\delta(1-r)\pi^*_{LI}+R_Iq_H\right]^2>0.$$

If $(1-R_I)q_H-\delta(1-r)\pi^*_{LI}<0$, we have $\Pi_H(P_H;0)\leq\delta(1-r)\pi^*_{LI}+R_Iq_H$. It suffices to have

$$\Pi_H(\widehat{P}_H;1)-[\delta(1-r)\pi^*_{LI}+R_Iq_H]>0.$$

Last, the proof of equilibrium uniqueness and the proof that the specified belief survives the intuitive criterion can be shown by the same logic in the Proof of Proposition 3 and thus omitted.

Lastly, we prove the comparative statics as follows.

In case (a) when $0<\delta<4/5$, or $4/5\leq\delta<2(\sqrt{2}-1)$ and $\frac{\sqrt{5\delta-4}(3\delta-2+\sqrt{\delta(5\delta-4)})}{2\sqrt{\delta}(1-\delta)}<r<1$, the price distortion in Costly Separating equilibrium is

$$\Delta P_{HIa}=\widehat{P}_{HIa}-P^*_{HIa}=\frac{-(1-R_I)(q_H-q_L)+\sqrt{[(1+R_I)q_L+\delta(1-r)\pi^*_{HI}]^2-4\Pi^*_{LIa}q_L}}{2}.$$

Then we have

$$\begin{aligned} &\left.\frac{d\Pi_H(\widehat{P}_{HIa};1)}{dr}\right|_{r=0}=-\frac{2}{q_H}\Delta P_{HIa}\left.\frac{d\Delta P_{HIa}}{dr}\right|_{r=0} \\ &=\left(\Delta P_{HIa}\big|_{r=0}\right)\frac{(q_H-q_L)(2-\delta)\delta\left(4(1-\delta)q_L+\delta q_H-\sqrt{(q_H-q_L)(\delta q_H+(8-7\delta)q_L)}\right)}{8(1-\delta)^2\sqrt{(q_H-q_L)(\delta q_H+(8-7\delta)q_L)}q_H}>0, \end{aligned}$$

which also implies that $\frac{d\Delta P_{HIa}}{dr}\Big|_{r=0} < 0$ because $\Delta P_{HIa} > 0$.

In case (b) when $4/5 \leq \delta < 2(\sqrt{2}-1)$ and $0 \leq r < \frac{\sqrt{5\delta-4}(3\delta-2+\sqrt{\delta(5\delta-4)})}{2\sqrt{2}(1-\delta)}$, or $2(\sqrt{2}-1) \leq \delta < 1$, the price distortion in Costly Separating equilibrium is

$$\Delta P_{HIb} = \widehat{P}_{HIb} - P^*_{HIb} = \frac{(1-R_I)q_L - \delta(1-r)\pi^*_{HI} + \sqrt{[(1+R_I)q_L + \delta(1-r)\pi^*_{HI}]^2 - 4\Pi^*_{LIb}q_L}}{2}.$$

Then we have

$$\begin{aligned}
\frac{d\Pi_H(\widehat{P}_{HIb};1)}{dr}\Bigg|_{r=0} &= -\frac{2\widehat{P}_{HIb} - (1-R_I)q_H - \delta(1-r)\pi^*_{HI}}{q_H}\frac{d\Delta P_{HIb}}{dr}\Bigg|_{r=0} \\
&\propto \frac{\delta(2-\delta)(q_H - q_L)}{16(1-\delta)^2}\left(\frac{\delta q_H + 4(1-\delta)q_L}{\sqrt{(\delta q_H + 4(1-\delta)q_L)^2 - 16\delta(1-\delta)q_L^2}} - 1\right) > 0,
\end{aligned}$$

which also implies that $\frac{d\Delta P_{HIb}}{dr}\Big|_{r=0} < 0$ since $\frac{2\widehat{P}_{HIb}-(1-R_I)q_H-\delta(1-r)\pi^*_{HI}}{q_H}\Big|_{r=0} > 0$.

By the continuity of $\widehat{\Pi}_{HIa}$ and $\widehat{\Pi}_{HIb}$ in r, there must exist a non-empty interval $0 < r < r''$ such that $\widehat{\Pi}_{HIa}$ and $\widehat{\Pi}_{HIb}$ increase with r. □

Proof in Positive Salvage Value

What we want to prove is summarized in the following lemma.

Lemma OA1. *Given any parameters (q_j, r, δ), there exists a unique function $V : [0,1] \to \mathrm{R}$ that satisfies equation (4).*

Proof. Let $\mathcal{B}$ be the space of functions $V : [0,1] \to \mathrm{R}$ with the sup norm $\eta : \mathcal{B} \to \mathrm{R}$, i.e., $\eta(V) = \sup_{\theta\in[0,1]} |V(\theta)|$. For any $V_1, V_2 \in \mathcal{B}$ and $\theta \in [0,1]$, we define the measure d as $d(V_1, V_2) = ||V_1 - V_2|| = \max_{\theta\in[0,1]} |V_1(\theta) - V_2(\theta)|$. Then for $x \in [0,1]$, we have

$$V_1(x) \leq V_2(x) + ||V_1 - V_2||.$$

Let $\mathcal{T}$ be the operator associating to any $V \in \mathcal{B}$ the function $\mathcal{T}V$. The equilibrium is a fixed point of the operator $\mathcal{T}$. It suffices to prove that there exists a constant $c \in (0,1)$ such that for any $V_1, V_2 \in \mathcal{B}$, $||\mathcal{T}V_1 - \mathcal{T}V_2|| \leq c||V_1 - V_2||$. Formally, we have

$$\begin{aligned}
\mathcal{T}V_1(x) &= \sup_{y\in[0,1]} (1-r)(1-y)(yq_j + \delta V_1(y)) + y\beta x q_j \\
&\leq \sup_{y\in[0,1]} (1-r)(1-y)(yq_j + \delta V_2(y)) + y\beta x q_j + \delta(1-r)||V_1 - V_2|| \\
&\leq \mathcal{T}V_2(x) + \delta(1-r)||V_1 - V_2||,
\end{aligned}$$

which implies $\mathcal{T}V_1(x) - \mathcal{T}V_2(x) \leq \delta(1-r)||V_1 - V_2||, \forall x \in [0,1]$. Similarly, we have $\mathcal{T}V_2(x) - \mathcal{T}V_1(x) \leq \delta(1-r)||V_1 - V_2||, \forall x \in [0,1]$. This implies that

$$||\mathcal{T}V_1(x) - \mathcal{T}V_2(x)|| \leq \delta(1-r)||V_1(x) - V_2(x)||, \forall x \in [0,1],$$

where $\delta(1-r) < 1$. $\square$

Proof of Proposition 10: Endogenous Popularity and Belief Cascade

Proof. We prove this proposition in three steps. First, we show that there is no pooling equilibrium surviving the intuitive criterion. Second, we characterize the unique separating equilibrium. Third, we show the effect of royalty rate.

Step 1: We show that under incomplete information, there does not exist a pooling equilibrium that survives the intuitive criterion.

We prove this argument by contradiction. Suppose a pooling equilibrium exists. Then, in resale markets, the popularity of artwork is $\overline{q} = \overline{q}(\lambda) = \lambda q_H + (1-\lambda)q_L$, the expected resale profit is $\overline{\pi} = \overline{\pi}(\lambda) = \frac{\lambda q_H + (1-\lambda)q_L}{[1+\sqrt{1-(1-r)\delta}]^2}$, and the expected royalties is $R\overline{q}$, where $R = \frac{r\delta}{(1+\sqrt{1-(1-r)\delta})(1-\delta+\sqrt{1-(1-r)\delta})}$.

We first characterize the buyer 0's purchasing decision and transaction probability in the primary market. For the j-type artist, buyer 0 will purchase if and only if $\theta_0 q_j - P + \delta(1-r)\overline{\pi}(\lambda) \geq 0$, which implies that the j-type artist's transaction probability is

$$D_j(P;\lambda) = \begin{cases} 1 & 0 \leq P < \delta(1-r)\overline{\pi}(\overline{\lambda}), \\ 1 - \frac{P-\delta(1-r)\overline{\pi}(\overline{\lambda})}{q_j} & \text{if} \quad \delta(1-r)\overline{\pi}(\overline{\lambda}) \leq P < \delta(1-r)\overline{\pi}(\overline{\lambda}) + q_j, \\ 0 & \text{otherwise.} \end{cases} \tag{OA2}$$

Suppose there exists a pooling equilibrium with price $\widetilde{P} < \delta(1-r)\overline{\pi}(\lambda) + q_L$. We need to consider two cases.

(a) For $0 \leq \widetilde{P} < \delta(1-r)\overline{\pi}(\lambda)$, the two types of artists' profits are

$$\Pi_L(\widetilde{P};\lambda) = \widetilde{P} + R\overline{q}(\lambda), \text{and} \ \ \Pi_H(\widetilde{P};\lambda) = \widetilde{P} + R\overline{q}(\lambda).$$

We consider an off-equilibrium-path price $P_o > \delta(1-r)\overline{\pi}(1) > \widetilde{P}$ such that $\Pi_L(P_o;1) = \Pi_L(\widetilde{P};\lambda)$, then we have

$$\Pi_H(P_o,1) - \Pi_H(\widetilde{P},\lambda) = \frac{q_H - q_L}{q_H q_L}(P_o + Rq_H)\left[P_o - \delta(1-r)\overline{\pi}(1)\right] > 0.$$

Therefore, $P' = P_o + \epsilon$ with sufficiently small $\epsilon > 0$ satisfies $\Pi_L(P';1) < \Pi_L(\widetilde{P};\lambda)$ and $\Pi_H(P';1) > \Pi_H(\widetilde{P};\lambda)$, which violates the intuitive criterion.

(b) For $\delta(1-r)\overline{\pi}(\lambda) \leq \widetilde{P} < \widetilde{P} < \delta(1-r)\overline{\pi}(\lambda) + q_L$, the two types of artists' profits are

$$\Pi_L(\widetilde{P};\lambda) = \left(\widetilde{P} + R\overline{q}(\lambda)\right)\left(1 - \frac{\widetilde{P} - \delta(1-r)\overline{\pi}(\lambda)}{q_L}\right),$$

$$\text{and} \ \ \Pi_H(\widetilde{P};\lambda) = \left(\widetilde{P} + R\overline{q}(\lambda)\right)\left(1 - \frac{\widetilde{P} - \delta(1-r)\overline{\pi}(\lambda)}{q_H}\right).$$

We consider an off-equilibrium-path price $P_o > \widetilde{P}$ such that $\Pi_L(P_o;1) = \Pi_L(\widetilde{P};\lambda)$, then we have

$$\Pi_H(P_o;1) - \Pi_H(\widetilde{P};\lambda) = (\Pi_H(P_o;1) - \Pi_L(P_o;1)) - (\Pi_H(\widetilde{P};\lambda) - \Pi_L(\widetilde{P};\lambda))$$
$$= \frac{q_H - q_L}{q_H}\left[(P_o - \widetilde{P}) + R(q_H - \overline{q}(\lambda))\right] > 0.$$

Therefore, $P' = P_o + \epsilon$ with sufficiently small $\epsilon > 0$ satisfies $\Pi_L(P';1) < \Pi_L(\widetilde{P};\lambda)$ and $\Pi_H(P';1) > \Pi_H(\widetilde{P};\lambda)$, which violates the intuitive criterion.

Step 2: We prove the existence and the uniqueness of separating equilibrium.

A key difference between this extension and the main model is on the low-type artist's mimicking incentive. In this extension, mimicking the high-type one's price not only improves buyer 0's expected resale value, but also all following buyers' beliefs and thus the artist's expected royalty income.

First, we prove that the equilibrium prices constitute a PBE. In any separating equilibrium, the low-type artist charges the optimal price under complete information P_L^*. If the optimal price under complete information can constitute a separating equilibrium, we have

$$\Pi_L(P_H^*;1) \le \Pi_L(P_L^*;0) \Leftrightarrow \frac{q_H}{q_L} \ge k_C(\delta,r) \equiv \frac{r^2\delta + 2(2(1-\delta)+r\delta)\sqrt{1-(1-r)\delta}}{4(1-\delta)^2 + 4(1-\delta)r\delta + \delta r^2}.$$

Otherwise, if $q_H/q_L < k_C(\delta,r)$, we must have $\Pi_L(P_H;1) \le \Pi_L(P_L^*;0)$, which is equivalent to

$$P_H \ge \widehat{P}_{HC} = \frac{[q_L + \delta(1-r)\pi_H^* - Rq_H] + \sqrt{[q_L + \delta(1-r)\pi_H^* + Rq_H]^2 - 4\Pi_L^* q_L}}{2}$$
$$\text{or } P_H \le \widehat{P}''_{HC} = \frac{[q_L + \delta(1-r)\pi_H^* - Rq_H] - \sqrt{[q_L + \delta(1-r)\pi_H^* + Rq_H]^2 - 4\Pi_L^* q_L}}{2},$$

where $\widehat{P}_{HC} > P_H^*$.

Second, we show that for any off-equilibrium-path price, the high-type artist cannot make a profitable deviation under the specified off-equilibrium-path belief. If $q_H/q_L \ge k_C(\delta,r)$, the equilibrium price is the optimal one under complete information, and thus high-type artist does not deviate. If $q_H/q_L < k_C(\delta,r)$, we can show that $\Pi_H(\widehat{P}_H;1) \ge \max_{P_H}\Pi_H(P_H;0)$. Following the transaction probability in equation (OA2), the high-type artist's profit under belief $\lambda = 0$ is

$$\Pi_H(P_H;0) = \begin{cases} P_H + Rq_L & \text{if } 0 \le P_H < \delta(1-r)\pi_L^*, \\ (P_H + Rq_L)\left(1 - \frac{P_H - \delta(1-r)\pi_L^*}{q_H}\right) & \text{if } \delta(1-r)\pi_L^* \le P_H < \delta(1-r)\pi_L^* + q_L \end{cases},$$

It suffices to have $\Pi_H(\widehat{P}_H;1) - \frac{1}{4q_H}\left[q_H + \delta(1-r)\pi_L^* + Rq_L\right]^2 > 0$

Lastly, the proof of equilibrium uniqueness and the proof that the specified belief survives the intuitive criterion can be shown by the same logic in the proof of Proposition 3 and thus is omitted.

By comparing $\widehat{P}_{HC}$ with the high-type artist's price under Costly Separating in the main model, $\widehat{P}_H$, we have

$$
\begin{aligned}
&\widehat{P}_{HC} > \widehat{P}_H \\
\Leftrightarrow&\sqrt{[q_L + \delta(1-r)\pi_H^* + Rq_H]^2 - 4\Pi_L^* q_L} > R(q_H - q_L) + \sqrt{[(1+R)q_L + \delta(1-r)\pi_H^*]^2 - 4\Pi_L^* q_L} \\
\Leftrightarrow&(1+R)q_L + \delta(1-r)\pi_H^* > \sqrt{[(1+R)q_L + \delta(1-r)\pi_H^*]^2 - 4\Pi_L^* q_L}
\end{aligned}
$$

which can be shown to be true.

Step 3: We show the effect of royalty on high-type's price distortion and profit in equilibrium.

In the Costly Separating equilibrium, the high-type's price distortion is

$$
\Delta P_C = \widehat{P}_{HC} - P_H^* = \frac{q_L - q_H + \sqrt{[q_L + \delta(1-r)\pi_H^* + Rq_H]^2 - 4\Pi_L^* q_L}}{2},
$$

we have

$$
\begin{aligned}
\frac{d\Delta P_C}{dr} &\propto \frac{d\left([q_L + \delta(1-r)\pi_H^* + Rq_H]^2 - 4\Pi_L^* q_L\right)}{dr} \\
&= -\frac{r\delta^3[q_L(q_H - q_L) + \delta(1-r)(\pi_H^* q_H - \pi_L^* q_L) + R(q_H^2 - q_L^2)]}{\sqrt{1-(1-r)\delta}[1+\sqrt{1-(1-r)\delta}]^2(1-\delta+\sqrt{1-(1-r)\delta})^2} < 0.
\end{aligned}
$$

The high-type artist's profit in Costly Separating equilibrium is

$$
\widehat{\Pi}_{HC} = \frac{1}{q_H}\left[\left(\frac{(1+R)q_H + \delta(1-r)\pi_H^*}{2}\right)^2 - \Delta P_C^2\right].
$$

We have

$$
\begin{aligned}
\frac{d\widehat{\Pi}_{HC}}{dr} &= \frac{2}{q_H}\left[\left(\frac{(1+R)q_H + \delta(1-r)\pi_H^*}{2}\right)\frac{d((1+R)q_H + \delta(1-r)\pi_H^*)/2}{dr} - \Delta P_C \frac{d\Delta P_C}{dr}\right] \\
&< \frac{((1+R)q_H + \delta(1-r)\pi_H^*)}{q_H}\left[\frac{d((1+R)q_H + \delta(1-r)\pi_H^*)/2}{dr} - \frac{d\Delta P_C}{dr}\right] \\
&\propto \frac{[q_L(q_H - q_L) + \delta(1-r)(\pi_H^* q_H - \pi_L^* q_L) + R(q_H^2 - q_L^2)]}{\sqrt{[q_L + \delta(1-r)\pi_H^* + Rq_H]^2 - 4\Pi_L^* q_L}} - q_H < 0.
\end{aligned}
$$

□