A MODEL OF PRODUCT DESIGN AND INFORMATION DISCLOSURE INVESTMENTS

Completed Research Paper

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Abstract

As information availability for products and services is increasing and as consumers engage in more online search prior to purchase decisions, it is becoming more important for firms to know when to invest to reduce consumer uncertainty. We argue that today's firms should view product design and investments to reduce consumer uncertainty as an integrated process, which is in turn heavily influenced by how much information consumers can obtain independently, for example, by reading product reviews or through third party infomediaries. Using a game-theoretic model, we explain how product quality decisions influence future investments to reduce consumer uncertainty, and demonstrate how firms should take this dependency into account to avoid over-investing in quality. We also show that firms can free ride on the product information already available in the market by third-party infomediaries, and reduce their own disclosure investments. We show that this is especially true for lower quality firms.

Keywords: Consumer uncertainty, information disclosure, product quality, infomediaries

Introduction

A major activity in markets is the transfer of product information by firms and third-party intermediaries to consumers. In recent years, technology has offered firms new ways with which to improve consumer knowledge about their products. Vendors can now showcase video instructions of product use as Apple does for its laptop computers; they can introduce interactive applications to help buyers find their perfect product fit, as prescription eyeglasses retailer Warby Parker does with its virtual try-on application (Miller 2011); and can even employ technology that allows buyers to simulate the experience of owning the actual product, as gaming company Electronic Arts does with its playable demos and Microsoft has done with an HTML5 webpage that allows iPhone and Android users to experience the Windows Phone interface. These technologies make use of interactive media to take advantage of increasing consumer familiarity with the Internet.

Technology has also made it easy for consumers to acquire product information from independent third-parties (Montgomery et al. 2004). These infomediaries offer expert product evaluations (Chen and Xie 2005), aggregate consumer reviews (Koh et al. 2010), or educate consumers about the product category in general. Many retailers, such as Amazon and J&R Electronics, also offer consumer reviews and expert product evaluations. The social commerce trend, currently exemplified by firms such as Facebook and Pinterest, also allows consumers to share product information and assessments with one another. The consequences of this "*ambient information*" made available by third parties is that consumers have an important alternative source of product information and need not rely exclusively on information provided by the manufacturers.

The economic and social consequences of these trends are significant. By 2009, 2% of total retail sales in the USA, and 10-15% of retail sales that involve the Internet, including Research Online-Purchase Offline – ROPO, were the direct result of consumers engaging in search for product information. The total value of search activity, including consumer surplus, exceeded $80 Billion (McKinsey Global Institute 2011).

Although product videos, product simulators, playable demos and other similar technologies make it easier for firms to reveal product quality information to consumers, they can be expensive. For example, video game developers consider playable game demos as non-trivial investments (Crossley 2010) and Electronic Arts has openly discussed the possibility of charging $10-$15 per comprehensive game demo (Martin 2010), in order to justify the extra development costs. In fact, we collected data on 2196 PC games released between 1996 and 2005 and found that only 55% invested in creating a playable demo. Thus, firms have to determine when it is worthwhile to invest heavily in product information disclosure and, in particular, assess how ambient information available through infomediaries affects these decisions. Further, given the growing importance of information investments, these investments should be viewed as an integral part of the product design process. Firms have to determine how much to invest in quality given the subsequent cost of informing customers about these quality attributes. Consider a printer manufacturer who has recently released one high-end and one budget printer model. The firm needs to determine whether to invest in information disclosure for these products and, if so, whether to do so differently for the two models. Further, it needs to understand how to modify its decision in response to third-party expert reviews.

A recent real-world example is tied to problems facing computer processor designer AMD in 2008-09 (Vance 2011) (Stokes 2009). AMD was forced by changing consumer preferences to invest away from the "clock-speed" race, into designing products with improved mobile graphics and video. The firm believed that, should it go ahead with the investment, it would also need to invest heavily to inform customers about graphics and video support in its processor. For example, it would need to retrain its sales and marketing employees to be able to communicate the new processors' advantages to prospective customers. AMD needed to determine how much to invest in the new product design given the cost of retraining employees and rebranding the company. In also needed to know whether competition would intensify or weaken if the firm and its competitors started competing along a product dimension (graphics performance) for which limited ambient information exists, due to the absence of metrics that are widely familiar to end consumers.

The key managerial questions that we address in this paper are tied to product information disclosure in the presence of third-party infomediaries. First, we ask how firms should invest in informing consumers and, in particular, how product quality influences this decision. Second, we ask how firms should factor in the cost of future information disclosure when choosing product quality levels. Finally, we ask how ambient information from infomediaries affects the firm's disclosure investments.

In brief, in this article we show that firms should view product quality investments and information disclosure investments as an integrated process and that, by doing so, they should moderate quality investments. This is contrary to a naive argument that consumers under uncertainty might discount less the quality of those firms who have shown a willingness to invest in quality, thereby making it attractive to over-invest in quality. Further, we show that information availability by third parties allows firms to *free ride* (reduce their information disclosure investments), but surprisingly, that free riding is more attractive to lower quality firms. Others (Chang and Wildt 1994) have argued that high quality firms benefit more from de-emphasizing product information. A simplistic conclusion that it would be easier for a high-quality firm to de-emphasize product information when third parties already provide it, is shown to be wrong.

Related Literature

Much of the current research on the role and availability of product information traces back to the work of Grossman, Milgrom, and Hart (Grossman and Hart 1980) (Grossman 1981) (Milgrom 1981) and the "unraveling mechanism". The mechanism explains that high quality vendors first report their product quality in order to separate themselves from the group of vendors with unknown quality. That leaves another set of vendors as the highest quality vendors in the group that has not reported yet, giving them the incentive to report their quality in turn, and so on, until all but the lowest quality vendors have provided quality information. Grossman (1981) showed that a similar argument applies even to monopolists who will want to report all but the lowest possible product quality. Grossman & Hart argue that "*the buyers need not be particularly sophisticated or have repeated experience with the seller.*[...] *The buyer must just use the simple logic that the seller tries to be as optimistic as possible about his product subject to the constraint that he not lie"* (Grossman and Hart 1980).

Jovanovic (1982) and Shavell (1994) studied how vendors decide to inform consumers about their quality, when disclosure entails a costly investment. They used the unraveling mechanism to show that vendors will invest in disclosure only above a quality threshold that depends on the investment cost. Empirical support for the positive impact of higher quality to quality disclosure investments has been provided by (Mathios 2000). There are, however, arguments that claim the opposite, particularly when pricing is endogenous and can be an alternative signaling mechanism. Chang & Wildt (1994) designed a laboratory experiment where they show that "*price exerts a positive influence on perceived quality, [...] moderated by the importance and amount of intrinsic information*". The role of pricing as a signaling mechanism is well known (Wolinsky 1983) (Milgrom and Roberts 1986), but Chang & Wildt show that it can substitute costly quality disclosure. The authors recommend that leading brands de-emphasize product information and focus more on using prices as a signaling mechanism. In support of this view, Sun (2011) presents evidence that higher quality products offer fewer free trials.

There is also an extensive body of work on the impact of competition on quality disclosure. Jin (2005) observes that disclosure investments in the healthcare industry are lower in more competitive markets. However, Jin argues that because quality disclosure decisions are influenced by the underlying product quality, the manner in which competition impacts quality disclosure depends on the quality choices of vendors and manufacturers; since the literature makes "ambiguous predictions" on the impact of competition to product quality (Tirole 1988), the relationship between competition and quality disclosure also depends on a complex combination of factors.

Indeed, one the one hand, there is work that suggests that the presence of multiple firms sharpens the incentives for information revelation. This may be because under intense competition even small changes in quality perceptions become important (Stivers 2004), or because, when the market is unaware that the firms possess any new information, the announcement by one firm of news, signals to the market that other firms may also possess new information (Dye and Sridhar 1995). On the other hand, some researchers argue that as the number of firms increases, vendors avoid disclosing information that may actually sharpen the competition between them, especially if the information is related to production costs or demand functions that are privately known to oligopolists (Okuno-Fujiwara et al. 1990), or if the information revealed educates the consumers about the product category in general, in which case firms in more competitive markets will be less likely to disclose in order to prevent competitors from free riding on their efforts (Jin 2005).

On the same theme of firms trying to alleviate price competition by withholding product information, in (Hotz and Xiao 2010) and (Board 2009) we find duopoly models where, under certain conditions, a firm may choose to withhold quality information, even if it is costless and can actually improve consumers' perceptions about the firm's quality.

In summary, the vast majority of papers in the literature on uncertain quality attributes has treated firms' quality choices as exogenous and has not considered the role of ambient information on firms' decision to disclose quality attributes. Two notable exceptions are (Albano and Lizzeri 2001), where we find the first uncertainty model to include endogenous quality production in a monopoly setting, and (Chen and Xie 2005), that studies quality uncertainty and the role of infomediaries in a duopoly setting. However, in (Albano and Lizzeri 2001) buyers cannot be informed by sellers but only by infomediaries, and the article's applicability is somewhat limited to markets that require a certification authority, e.g., an auditor. In (Chen and Xie 2005) the authors focus solely on information disclosure and their model provides no insight to infomediaries' impact to product quality.

Analytical Model & Solution

Model and Game Set-up

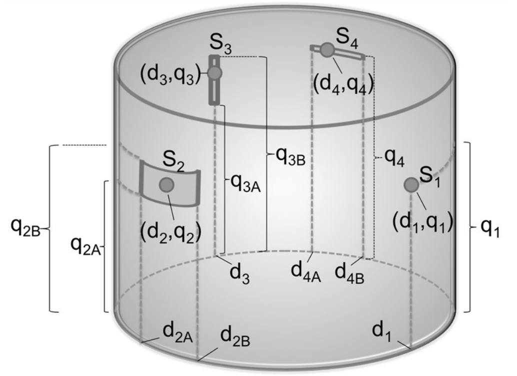

Figure 1. Our model of product differentiation and consumer uncertainty

We consider a market with N vendors in which products are characterized by one taste[1] and one quality characteristic. Following (Economides 1993), we represent this in the form of a cylindrical market (see Figure 1). The unit size circumference represents the taste (type) choices, while the cylinder's height is the quality attribute space. Figure 1 depicts four vendors S_1,S_2,S_3 & S_4 with $(d_i, q_i), i = 1 \dots 4$, as the type and quality of their products respectively. Vendor enumeration proceeds sequentially and vendors with sequential indexes are neighbors in the taste space.

We assume that buyers can obtain perfect information on product prices and vendor identities, but not so for product attributes, unless vendors actively invest in informing them. If the vendors do not invest in information disclosure, consumers can rely on the information that is made available by third party intermediaries. Buyers' priors regarding these uncertain attributes are represented as a probability distribution whose support includes the product's actual location, in both product dimensions. For example, in Figure 1 consumers perceive the quality of vendor S_2 as a random variable $\overline{q_2}$ with PDF $f_{q2}(\cdot)$,

[1] The terms *Taste* and *Type* are used interchangeably throughout the article. Economists also use the terms *Variety* and *Horizontal Differentiation*.

CDF $F_{q2}(\cdot)$ and support $[q_{2A}, q_{2B}]$. The interval $[q_{2A}, q_{2B}]$ is termed the "*quality uncertainty interval*" for seller S_2 and it has size $\alpha_q \equiv q_{2B} - q_{2A}$, which is the same for all sellers. Similarly the information about the type of vendor S_2 is perceived by buyers as a random variable $\overline{d_2}$ with PDF $f_{d2}(\cdot)$, CDF $f_{d2}(\cdot)$ and support $[d_{2A}, d_{2B}]$. The interval $[d_{2A}, d_{2B}]$ is termed the "*type uncertainty interval*" for seller S_2, with size $\alpha_d \equiv d_{2B} - d_{2A}$, which is the same for all sellers. Of course, $f_{qi}(\cdot)$ and $f_{di}(\cdot)$ are priors that may be rationally updated by the buyers, taking into account additional information, such as vendor disclosure decisions. Thus, buyers can and do consider uncertainty intervals of different sizes prior to their purchase decision. Further we will assume that $f_{qi}(\cdot)$ and $f_{di}(\cdot)$ are uniform and independent for all $i = 1 \ldots N$.

We do not require that uncertainty intervals are centered at the actual product location. For example a product whose actual quality is at the low end of its quality uncertainty interval, appears to prospective buyers to be better than it actually is. On the contrary, a product whose actual quality is at the high end of its quality uncertainty interval appears to be worse than it actually is. As more information about both products begins to become available, the expected quality of the first product would appear to reduce, while the expected quality of the second product would appear to increase. Both cases, as well as the case of expected product quality remaining constant when more information emerges, are easily observable in real markets. For example, in (Li and Hitt 2008), the authors document the wide difference between how books sold on Amazon are initially perceived by consumers when information (i.e., reviews) about them is relatively sparse, and how the same books are perceived in the long run steady state, when enough reviews have accumulated. We view books with steep, downward-adjusting average review, as books whose true quality happened to be at the high end of their initial quality uncertainty intervals.

If vendors are dissatisfied by the level of information that infomediaries provide, they can invest in information disclosure. In Figure 1, vendor S_2 has chosen to disclose neither his exact quality nor his exact type, vendor S_1 has disclosed his exact values on both dimensions (and is hence depicted as a dot), vendor S_3 has chosen to disclose full taste information but no quality information and vendor S_4 has disclosed full quality but no taste information. These four choices represent the disclosure decision space of the vendors.

All buyers demand one unit of the product. Each consumer is defined by his most preferred product location in the taste space *z*. Consumers are uniformly distributed around the cylinder's circumference in this respect. The value to the consumer of purchasing a product with characteristics (d_i, q_i) and price p_i is $V(z, d_i, q_i, p_i) = v + \theta \cdot q_i - p_i - t \cdot |z - d_i|$, where v is the consumer's utility from consuming a product at the minimum possible quality that is located at his most preferred type, θ denotes the intensity of the consumer's preference for quality, and t, the fit cost parameter, denotes the disutility that the consumer experiences from consuming a product that is not his ideal. The parameters t and θ are common to all buyers. A usual additional assumption in spatial models is that v is large enough (or, alternatively, t is small enough) so that all the market is served (Hotz and Xiao 2010) (Tirole 1988). This assumption is needed so that none of the vendors become a monopolist – a case that requires substantially different analysis, and is in fact pursued in a separate article. We provide the exact requirement for v after we have introduced all relevant notation and before the solution to the symmetric equilibrium, below.

The expected utility to a consumer with preferred product location $z \notin [d_{iA}, d_{iB}]$ from purchasing from vendor S_i, is given by $E(V) = v + \theta \cdot E(\overline{q_i}) - p_i - t \cdot |z - E(\overline{d_i})|$ where $E(\cdot)$ denotes expected value.

Let $r_i \in \{0, c_q\}$ denote the quality disclosure investment cost for vendor S_i, which is zero if the vendor does not release quality information and $c_q > 0$ otherwise. We assume convex costs of quality of the form $C(q_i) = kq_i^2/2$. Similarly $s_i \in \{0, c_d\}$ denotes type disclosure investment cost for Firm S_i. In addition, we assume that a firm's type or quality uncertainty is fully resolved upon investment by the firm. The revenue and profit functions for firm S_i in vector notation, are given by:

$$R_i(\mathbf{p}, \mathbf{q}, \mathbf{d}) = p_i \cdot D_i(\mathbf{p}, \mathbf{q}, \mathbf{d}), \quad \Pi_i(\mathbf{p}, \mathbf{q}, \mathbf{d}) = p_i \cdot D_i(\mathbf{p}, \mathbf{q}, \mathbf{d}) - C(q_i) - r_i - s_i \qquad \textbf{[1]}$$

where $\boldsymbol{p} = (p_1, p_2, \ldots, p_N), \boldsymbol{q} = (E(\overline{q_i}), E(\overline{q_2}), \ldots, E(\overline{q_N}))$, $\boldsymbol{d} = (E(\overline{d_i}), E(\overline{d_2}), \ldots, E(\overline{d_N}))$. Note that quality production cost depends on actual product quality, but demand depends on perceived quality.

We assume that vendors seek to maximize profits and that buyers seek to maximize their utility, and define our game as follows:

- **Stage 1**: All vendors choose their type.

- **Stage 2**: All vendors choose their level of quality investment (they thus choose their quality).
- Vendors learn how their own products are perceived by early users in pre-market trials. They thus learn the uncertainty intervals (chosen by nature) that will be associated with their products if they do not invest in information disclosure.
- **Stage 3**: All vendors make their decisions on whether to invest in information disclosure.
- All vendors and buyers learn the information of vendors who invested in disclosure and learn from infomediaries the uncertainty intervals of vendors who have not invested in disclosure.
- **Stage 4**: All vendors choose their price.
- Buyers enter the market and make their purchase decisions.

Note that since firms choose quality and type before they learn competitors' choices, they are in reality playing the first two stages simultaneously.

While this article focuses product quality, it also includes taste-related product attributes in order to be more realistic, and to avoid Bertrand-type competition among sellers with very similar qualities. Models that exclude the horizontal dimension often lead to perverse incentives towards quality investments, with vendors wanting consumers to discount their quality, if by doing so they prevent consumers from learning that their quality is very similar to a competitor, all in their effort to reach a separable equilibrium with positive profit. We focus on the case where uncertainty about horizontal attributes is relatively low. For obtaining a closed form solution of the equilibrium that is symmetric on product types, it suffices to assume $\alpha_d < 1/(2N)$, which is simple to show that translates to assuming that horizontal uncertainty intervals will never overlap (we allow this possibility for the quality uncertainty intervals).

The entire model is analytically solvable, and we provide in the Appendix, in condensed form, one subgame-perfect solution with symmetrically positioned products, that is, we provide the solution where the vendors have placed their products equidistantly in the taste space. We next proceed to derive the form of the profit function which suffices to intuitively understand all of the model results that follow.

Let the marginal consumer who is indifferent between vendors S_i and S_{i+1} have type z_i. Assuming $\alpha_d < 1/(2N)$, we can show that $z_i = \frac{E(\overline{d_i})+E(\overline{d_{i+1}})}{2} + \frac{p_{i+1}-p_i}{2t} + \frac{\theta(E(\overline{q_i})-E(\overline{q_{i+1}}))}{2t}$.

Repeating the calculation for z_{i-1}, we derive the demand $z_i - z_{i-1}$ for Firm S_i :

$$D_i = \frac{E(\overline{d_{i+1}}) - E(\overline{d_{i-1}})}{2} + \frac{p_{i+1} + p_{i-1} - 2p_i}{2t} + \frac{\theta(2E(\overline{q_i}) - E(\overline{q_{i+1}}) - E(\overline{q_{i-1}}))}{2t} \qquad \textbf{[2]}$$

Thus, a firm captures half the buyers that are in between its closest two competitors in the taste space (first term) adjusted for the price differential (second term) and the quality differential (third term). Note that a vendor's demand function, by Equation [2] is independent of his own choice of type d_i except in the sense that it determines the two closest competitors. Also note that arithmetic in the taste space is done modulo the unit circle. For example, the neighbors of firm S_N are firms S_{N-1} and S_1, and a distance $d_{i+1} - d_i$ is taken to be $1 + d_{i+1} - d_i$, if $d_{i+1} < d_i$.

Differentiating Equation [1] with respect to price: $p_i - \frac{(p_{i-1}+p_{i+1})}{4} = \frac{t(E(\overline{d_{i+1}})-E(\overline{d_{i-1}}))}{4} + \frac{\theta(2E(\overline{q_i})-E(\overline{q_{i+1}})-E(\overline{q_{i-1}}))}{4}$. Substituting into Equation [2] we get $D_i^* = p_i^*/t$ and thus:

$$\Pi_i^*(p_i^*, \mathbf{q}, \mathbf{d}) = p_i^{*2}/t - C(q_i) - r_i - s_i \qquad \textbf{[3]}$$

Results and Managerial Implications

Information Disclosure Investments

Proposition 1: Let $Pr_i(q_i)$ be the probability that vendor S_i will disclose, given quality q_i. Then $Pr_i(q_i)$ can only increase in q_i. Moreover, the relationship is continuous

Proof: Provided in the Appendix. The intuition is discussed below.

It is perhaps intuitively expected that the higher the quality of a product, the higher the vendor's profit, in case of disclosure. This is in general agreement with most literature on the topic (Jovanovic 1982; Farrell, 1986; Verrecchia 1983; Dye 1986; Shavell 1994). However, in the classic literature, the usual result is that there is a quality threshold, and only vendors beyond this threshold disclose (Jovanovic 1982). In our model, the probability of disclosure rises smoothly with quality, because the higher the expected quality of a product, the more the buyers will discount its quality, should the vendor fail to invest in information disclosure. For example: assume that buyers expect ex-ante that a vendor's quality is uniformly distributed between 4 and 5 units (expected quality is 4.5). Upon observing that the vendor has not disclosed, buyers discount his quality and form new expectations in the range of 4 to $5 - x$ units. Assume now that the buyers expect ex-ante that another vendor's quality is uniformly distributed between 2 and 3 units (expected quality is 2.5). Upon observing that the vendor failed to invest in quality disclosure, buyers discount the vendor's quality and form new expectations in the range 2 to $3 - y$ range, but now $y < x$.

While Proposition 1 is not entirely surprising, it is still useful to understand the intuition behind the result, and to also verify that real markets behave this way, because all results that follow depend on it.

As the derivation of Equation [3] shows, profits are convex in expected product quality because they are convex in price, and price increases proportionally with expected quality: $p_i \sim E(\overline{q_i})$. A more detailed explanation is that an increase in quality allows a vendor to increase his price (also see Equation [6] in the Appendix) while simultaneously gaining market share in the taste space (Equation [2]). With convexity, for a given quality improvement, a higher quality vendor increases profit more than a lower quality vendor does. Thus, a higher quality vendor would invest to improve buyers' perception even by a small amount, or equivalently, would invest to prevent even a small decrease of buyers' expectations about its quality. In other words, buyers argue that a higher quality vendor would surely, if he could, disclose to prevent them from forming an expectation for quality close to the lower limit of the uncertainty interval, while a lower quality vendor would not necessarily do so. Thus, a non-disclosing higher quality vendor reveals that he cannot prevent buyers from expecting quality at the lower end of the uncertainty interval, because this is actually where his true quality lies, and a disclosure would not help in his case.

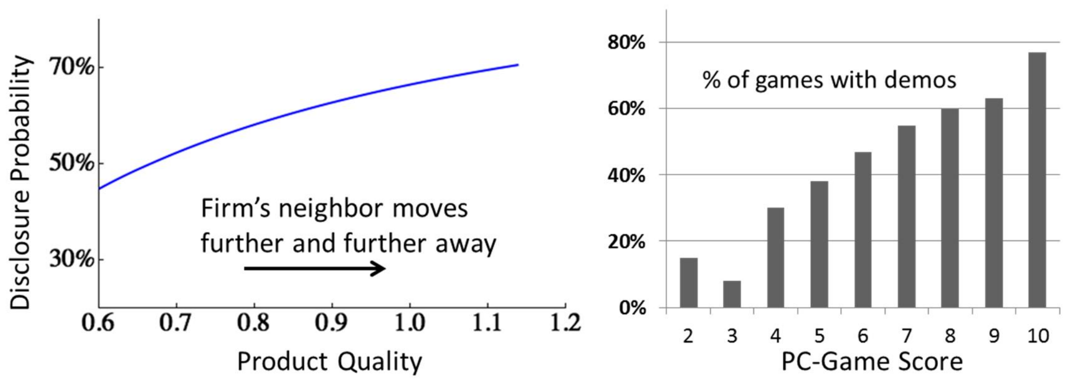

Figure 2. Disclosure probability as a function of product quality in our model and in a real market. Parameter values used are [$N = 3$ (which also implies $b = 0.8$), $t = 10, \theta = 5, k = 1.5, c_q = 0.1, \alpha_q = 0.4, a_d = 0.2$]

To demonstrate Proposition 1, we gathered data on 2,196 PC-games released between 1996 and 2005, from the gaming website GameSpot. Game developers had a choice to invest in developing playable demo versions of their games, which could reduce buyer uncertainty about the quality of the game but were also expensive to develop. On the left side of Figure 2, we plot disclosure probability for a firm under different quality levels[2], and on the right side we have plotted the percent of PC-games that have invested in

[2] Different equilibrium quality levels are derived from the general equilibrium solution which we omit for brevity, and where, other things equal, the further away a firm's neighbors, the higher the equilibrium

producing a playable demo version, for different game quality levels. The graph clearly shows that the higher the game quality, the greater the probability of the game developer having invested in the development of a playable demo version, and that there does not appear to be a quality threshold for disclosure, as the classic literature predicts. These results are robust to corrections for game genres and release dates.

The significance of the above is not immediately obvious. Why should a firm care if the probability that it will make a disclosure investment increases smoothly with product quality, and not in a discontinuous way? The answer is that this relationship between product quality and disclosure means that no matter what a product's quality is, a further improvement in quality will always carry an additional cost, related to a future need for an information investment. The next section explores this connection between quality production and disclosure.

Quality Production Decisions

Proposition 2: Quality investment under uncertainty is at most equal to equilibrium quality under perfect information[3]

Proof: Provided in the Appendix. The intuition is as follows:

We established that the probability of quality disclosure increases with product quality, because buyers discount the quality of a non-disclosing firm more at higher quality levels. Consequently, when a firm decides how much to invest in order to improve product quality, it has to account for its future expected quality disclosure costs. These future information disclosure investments act as a "hidden" quality production cost at the stage of product design and when taken into account lead to lower optimal quality, compared with the quality that a firm would have chosen under a perfect information regime.

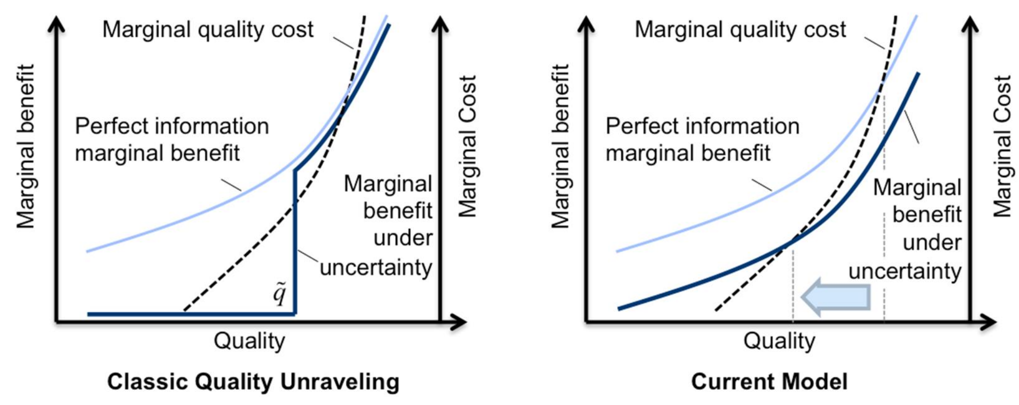

Figure 3. The mechanism of quality production in our model, as a refinement of the classic literature

Figure 3 explains how quality production in our model differs from classical quality unraveling, where firms invest in quality disclosures only above a certain quality threshold. The figure shows the marginal benefit and the marginal cost of quality under perfect information and under uncertainty, where marginal benefit is defined simply as marginal profits minus the marginal quality disclosure cost, and are derived by differentiating $p_i^{*2}/t - r_i - s_i$ (from Equation [3]) and $C(q_i) = kq_i{}^2/2$ with respect to quality. Obviously, for every firm, equilibrium quality production is determined by the point where the marginal benefit of an additional quality increase, matches the marginal quality production cost. Under classical quality unraveling, firms disclose quality only above a threshold $\tilde{q}$. Thus, on the left graph of Figure 3, the

quality of the firm.

[3] The idea of quality underinvestment under uncertainty was first discussed in (Jovanovic 1982), but was first shown explicitly by Albano & Lizzeri (Albano and Lizzeri 2001).

marginal benefit of increasing quality at any quality level below the disclosure threshold $\tilde{q}$, is zero, since quality below the threshold will not be disclosed and any quality improvement will go undetected with buyers assuming the worst possible product quality. However, the marginal benefit of increasing quality when already above the disclosure threshold $\tilde{q}$, is the same as the perfect information case, as quality will always be disclosed above the threshold. Therefore, with classical quality unraveling, optimal quality is either at its minimum level, or it is the same as the quality under perfect information, depending on whether or not the marginal cost curve meets the marginal benefit curve above the threshold. In the current model, the marginal benefit of increasing quality lies below the marginal benefit under perfect information and non-zero disclosure probability, as we have seen in the previous section that any quality increase also increases the chances that a quality disclosure cost will be incurred. Therefore, compared to the perfect information case, our model predicts that firms will produce lower quality levels under uncertainty, as shown by the arrow on the right of Figure 3.
An example where firms have been found to invest less in quality under uncertainty, concerns hygiene in the Los Angeles restaurant market, and has been documented in (Jin and Leslie 2003). Prior to 1998, restaurants were not required to disclose their hygiene inspection results or to use any particular format when doing so. In 1998 a standardized report card was introduced that made reporting of hygiene inspections easily understood and comparable across all restaurants in all L.A. county cities. Each county city was then left to decide on whether or not to force their restaurants to prominently display these report cards. For mandatory disclosure cities, the result was a transition to a perfect information regime, since any quality disclosure costs become sunk as mandatory. For voluntary disclosure cities, the result was a reduction of the quality disclosure cost, since standardization had dramatically reduced the cost of explaining to consumers what the hygiene level of a restaurant was, compared with other restaurants in the area. This is equivalent to an upwards shift of the marginal benefit curve in the right hand side of Figure 3, very close to the perfect information marginal curve, which should also lead to an increase in quality (recall that disclosure costs are included in the marginal benefit). Indeed, Jin & Leslie documented the subsequent increase in the hygiene levels on both mandatory and voluntary disclosure cities, as captured by increasing inspection scores, and also by the reduction of food-related hospital admissions in L.A. county.

The managerial implication is that firms must include the cost of future information disclosure in their quality production 'Return on Investment' (ROI) calculations; higher quality levels increase the probability that firms will also need a quality disclosure investment. In other words, quality is more expensive than it appears due to consumer uncertainty. Consider our prior example about AMD. When AMD chose to implement a significant quality improvement, it also ended up having to invest heavily in a yearlong program to retrain all of its retail sales representatives "*in the art of marketing visual performance*" (Vance 2011). The practical implication for every manager calculating the ROI of a quality improvement project, is that on the cost side, along with items that are usually accounted for, such as more costly materials, more expensive Quality Assurance, and new feature design and development costs, the manager must also include an expected information disclosure cost, because such a cost is the direct result of the contemplated quality increase. Moreover, the larger the quality improvement under consideration, the larger the information disclosure cost that must be accounted for in the ROI calculation.

Impact of Ambient Information on Firm's Information Investments

Proposition 3: $Pr_i(q_i)$ decreases as α_q decreases. That is, firms disclose less as ambient market information increases.

Proof: Follows directly from Lemma 7, in the Appendix. The intuition is discussed below.

Firms' investments to reduce consumer uncertainty naturally depend on the amount of ambient information available in the market. Infomediaries, consumer reviews, press coverage, and other third party sources of product information contribute to consumer informedness, often allowing firms to free ride on this ambient information, and forgo their own information disclosure investments. However, as infomediaries provide more and more information, the sizes of uncertainty intervals that consumers can assign to different products reduces, and the potential for consumers to discount the quality of a vendor who does not disclose diminishes, making non-disclosure less costly.

Google appears to have used increased information availability by third-parties, to reduce its own information disclosure costs. In 2003 the company created a community (Google Forums) where its customers could answer each other's questions about the company's AdWords product. This allowed Google to stop providing product information itself and to forgo the ongoing investment that would be required to fully inform the hundreds of thousands of customers on product features and use (Levy 2011). Today, Google Product Forums have been expanded to include all of the company's products.

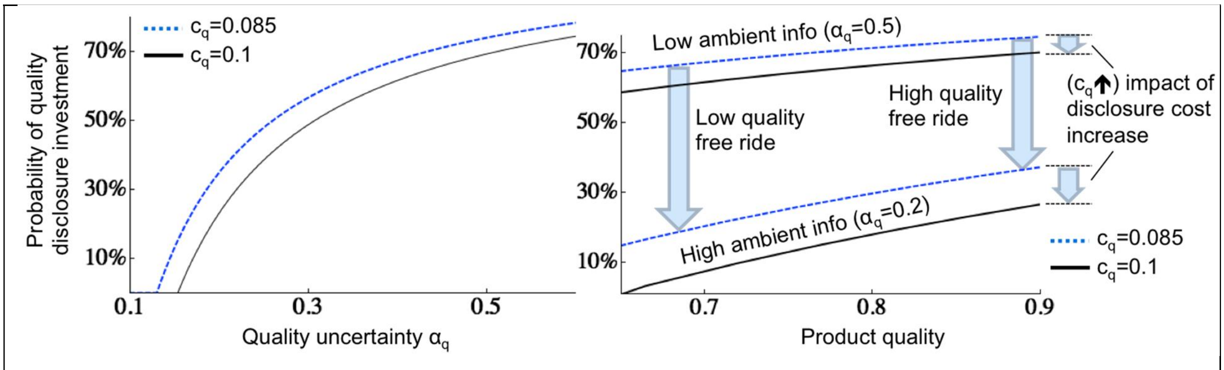

Figure 4. Ex-ante probability of quality disclosure investments as a function of quality uncertainty in the symmetric equilibrium (left) and equilibrium quality in a general equilibrium (right). Parameter values used are [$N = 3$ (which also implies $b = 0.8$), $t = 10, \theta = 5, k = 1.5, c_q = 0.1, \alpha_q = 0.4, a_d = 0.2$]

Mathematically, the probability that a firm will disclose decreases, as quality uncertainty decreases. This is depicted on the left side of Figure 4 where we plot the (ex-ante) probability that a firm will invest in information disclosure for the case of symmetric firm types, as given in Lemma 7. No firm discloses when α_q is below a certain threshold relative to the quality disclosure cost, given by Lemma 8[4].

Further, our model shows that the opportunity for firms to free ride on ambient information and forgo their own information disclosure investments is relatively greater for lower quality vendors, than it is of higher quality vendors. This is depicted on the right side of Figure 4. As the two longer arrows show, when third parties increase the amount of ambient information availability (α_q decreases from 0.5 to 0.2), the probability that firms disclose reduces. In other words, firms free ride on the information provided by third parties. But note also that of the two arrows, the one on the left, where product quality is lower, is longer than the one on the right. In other words, it is easier for lower quality vendors to free ride on third party information. On the contrary, higher quality firms should be more careful and should not be as easily content as lower quality firms with consumers relying on third party infomediaries.

Formally:

Proposition 4: The reduction in the vendors' (ex-ante) probability of quality disclosure as α_q decreases, is greater (in absolute value) at lower product qualities. Mathematically, let $Pr_i(q_i, a_q)$ be the probability that vendor S_i will disclose, given quality q_i and quality uncertainty a_q, and let x be a positive constant. Then $Pr_i(q_i, a_q) - Pr_i(q_i, a_q - x)$ decreases as q_i increases.

Proof: From Lemma 7 in the Appendix, and also using Lemma 1, it can easily be shown by differentiation that at all product quality levels the derivative of the probability of disclosure with respect to product quality, decreases as α_q increases. Proposition 4 is now implied, as the probability of disclosure as a function of quality will always be steeper at lower α_q.

The intuition behind this result is that any increase in quality reduces a firm's disclosure threshold inside its quality uncertainty interval. When the uncertainty interval is relatively small (high ambient

4 The threshold, described in Lemma 8, decreases in *N*, so that fewer firms disclose with more competition. This agrees with prior work (Hotz and Xiao 2010; Okuno-Fujiwara et al. 1990; Cheong and Kim 2004) and is empirically supported by Jin (Jin 2005).

information), even a small decrease in the position of the disclosure threshold can significantly affect the probability that a firm's quality will be below (or above) the threshold. Thus, the probability of a disclosure investment becomes more sensitive on quality when α_q is low, as can be seen on the right side of Figure 4 where the bottom pair of lines is steeper. But, obviously, this means that the two pairs of lines should converge towards higher qualities, which means that free riding on ambient information should be less pronounced in higher qualities.

We find empirical evidence for the validity of Propositions 3 and 4 in (Chen and Xie 2005). The authors looked at how firms adjust their advertising spending as a response to an independent product review published in a magazine. They observed reviews that discuss product quality and end in a recommendation (or not). As per our analysis, we would expect firms to respond to a third party review by reducing the amount of information they disclose. Further, lower quality firms should reduce their disclosure spend, more than higher quality firms. This is indeed what Chen & Xie found. Higher quality printers did not significantly change their advertising spend, while lower quality printers did. In a different product category, lower quality running shoes reduced their advertising spend, as a response to a product review, by 71%, compared to 30% reduction for high quality running shoes.

Concluding Remarks

The rising popularity of electronic markets has increased the significance of firms' investments to reduce consumer uncertainty about their products. In this paper, we investigate both the process of product design, and the subsequent product information investments. Specifically we employ a game theoretic model of an oligopolistic market where product design and product information investments are endogenous decision variables, affected by information made available by third parties.

We show that it is important for managers to consider the processes of product design and of investing to reduce consumer uncertainty as a single integrated process, that is in turn affected by the amount of information that is available to consumers by third-parties. Specifically, we offered managers three pieces of advice.

First, firms that invest to reduce consumer uncertainty should account for their product quality. This is because buyers discount the quality of firms who do not invest to reduce consumer uncertainty. In the case of high quality firms, buyers' discount for non-disclosure is even larger; such firms have more to lose when they fail to invest in technology designed to improve consumers' knowledge about their products.

Second, firms that invest to improve their product quality should also account for the possibility that, in the future, they may also have to invest to reduce consumer uncertainty about their quality. This is because the higher the level of the quality that a firm produces, the more likely it is that it will incur a future quality disclosure cost. Few firms today appear to heed this piece of advice, and this is a costly omission on their part. The forward-looking managers that follow this recommendation account for the way that today's quality investment impact tomorrow's quality disclosure investments. Their firms moderate their level of quality in the presence of uncertainty, and avoid overinvesting in quality improvements.

Finally, firms that invest to reduce consumer uncertainty should consider whether the information that buyers can receive from third parties is already sufficient. As third party infomediaries proliferate, this advice is increasingly relevant. Indeed, a firm may be able to free ride on such ambient information availability and forgo costly information investments. We showed that the opportunity to free ride is greater for lower quality firms. Higher quality firms should be more careful and should not be as easily content as lower quality firms with consumers relying on third party infomediaries.

While the idea that the processes of product design and information disclosure investments should be integrated and account for information availability by third parties, has been demonstrated to be theoretically sound, much more work is needed before it can actually inform managerial decisions. Detailed empirical and experimental investigation is required to verify the applicability of the article's theoretical recommendations, and much additional work is required to specify how these recommendations can be made actionable and practical.

Table of Mathematical Notations	
Symbol	**Definition**
Decision Variables	
q_i, d_i, p_i	Firm S_i's chosen quality, type, and price respectively
r_i, s_i	Firm S_i's quality & type disclosure cost. $r_i \in \{0, c_q\}$, $s_i \in \{0, c_d\}$
Model parameters	
N	Number of firm in the market
v	Buyer utility for product of zero quality located at his most preferred type
$\overline{q_i}$, $\overline{d_i}$	Random variables that correspond to q_i and d_i under imperfect information
$f_{qi}, f_{di}, F_{qi}, F_{di}$	PDFs & CDFs of $\overline{q_i}$ and $\overline{d_i}$
$[q_{iA}, q_{iB}], [d_{iA}, d_{iB}]$	Quality & type uncertainty intervals. Non-zero regions (support) of f_{qi}&f_{di}
c_q, c_d	Cost for disclosing quality & type, respectively
θ, t	The intensity of consumer preference for quality & type, respectively
$C(q_i), k$	$C(q_i)$ is the quality production cost and equals: $C(q_i) = kq_i^2/2$
Derived values	
α_q, a_d	Sizes of the quality & type uncertainty intervals, respectively.
z_i	Most preferred location of buyer who is indifferent between Firms i and i+1
q, d	Vectors of expectations for q_i and d_i for all vendors
$\widetilde{q_i}$, $\underline{q_i}$	Value of q_i, above which quality is disclosed, and $E(\overline{q_i} \mid \overline{q_i} < \widetilde{q_i})$
δ_i	$\delta_i = \widetilde{q_i} - \underline{q_i}$. Equals half the disclosure range for uniform f_{qi}
p_i, R_i, D_i, Π_i	Firm S_i's product price, revenue, unit demand, and profit, respectively
p	Vector of prices for all firms
x	Vector with $x_i(\mathbf{d}) = \left(E(\overline{d_{i+1}}) - E(\overline{d_{i-1}})\right)/4$. Used for notational convenience
$\mathbf{A}, \mathbf{A}^{-1}$	Symmetric circulant matrices. $\boldsymbol{A}[i,i] = 1, \boldsymbol{A}[i+1,i] = -1/4$ & zeros elsewhere
H	Matrix $\mathbf{H} = \mathbf{A} - \mathbf{I}/2$. Used for notational convenience
b_i, b	b_i is element of the diagonal of $\mathbf{A^{-1}}$ at distance *l* from main diagonal; b is $b_0 - b_1$
e	Vector defined as $\mathbf{e} \equiv t \cdot \mathbf{x}(\mathbf{d}) + \theta \cdot \mathbf{H} \cdot \mathbf{q}$. Used for notational convenience
$Pr_i(\cdot)$	The probability that firm S_i will invest in quality disclosure, when uncertainty intervals are not yet known

Appendix of Proofs and derivations

i. The Pricing Stage

We only present the analysis of the equilibrium where product types are symmetric around the circle. The analysis for the general equilibrium form that includes non-symmetric firms, is omitted for brevity.

In the pricing subgame, vendors have already chosen their product details and have made their disclosure decisions. Vendor S_i maximizes profits with respect to price p_i (Equation [1]) when:

$p_i - \frac{p_{i-1}}{4} - \frac{p_{i+1}}{4} = \frac{t}{4}\left(E\left(\overline{d_{i+1}}\right) - E\left(\overline{d_{i-1}}\right)\right) + \frac{\theta}{4}\left(2E(\overline{q_i}) - E(\overline{q_{i+1}}) - E(\overline{q_{i-1}})\right)$. In matrix form:

$$\mathbf{A} \cdot \mathbf{p} = t \cdot \mathbf{x} + \theta \cdot \mathbf{H} \cdot \mathbf{q} \qquad \textbf{[4]}$$

where matrix $\mathbf{A}$ has $\mathbf{A}_i = [A_{i,1} = 0, A_{i,2} = 0, \ldots, A_{i,i-1} = -\frac{1}{4}, A_{i,i} = 1, A_{i,i+1} = -\frac{1}{4}, \ldots, A_{i,N} = 0]$, $\mathbf{x}$ is the vector with $x_i = \left(E\left(\overline{d_{i+1}}\right) - E\left(\overline{d_{i-1}}\right)\right)/4$, $\mathbf{q}$ is the vector with $\mathbf{q}_i = E(\overline{q_i})$, and $\mathbf{H} = \mathbf{A} - \mathbf{I}/2$, with $\mathbf{A}$, $\mathbf{H}$ circulant symmetric matrices of constants, which means that the inverse of $\mathbf{A}$ exist, as long as the first row sums up to a non-zero constant, as is the case here.

Since $\mathbf{A}$, $\mathbf{H}$ are invertible, Equation [4] has a unique solution with

$$\mathbf{p}^*(\mathbf{q}, \mathbf{d}) = \mathbf{A}^{-1}(t \cdot \mathbf{x}(\mathbf{d}) + \theta \cdot \mathbf{H} \cdot \mathbf{q}) \equiv \mathbf{A}^{-1} \cdot \mathbf{e}(\mathbf{q}, \mathbf{d}) \qquad \textbf{[5]}$$

Letting b_k denote the element of the diagonal at distance $|k|$ from the main diagonal of $\mathbf{A}^{-1}$, then:

$$p_i^* = \sum_{j=-N/2}^{N/2} b_j e_{j+i}(\mathbf{q}, \mathbf{d}) \qquad \textbf{[6]}$$

The next two lemmas explain how equilibrium price responds to changes in expected quality. Intuitively, the lemmas show that an increase in expected quality allows a vendor to increase his equilibrium price, but an increase in the expected quality of a competitor, forces a vendor to reduce his equilibrium price by an amount that depends on how close a neighbor (in the taste space) that competitor is. Closer taste-space neighbors have greater impact on each other's prices.

Lemma 1: $dp_i^*/dE(\overline{q_i}) = \theta \cdot b/2, \textit{where } b = b_0 - b_1$

Proof: $dp_i^*/dE(\overline{q_i}) = \sum_{j=N/2}^{N/2} b_j\left(de_{i+j}(\mathbf{q}, \mathbf{d})/dE(\overline{q_i})\right) = b_0\theta/2 - b_1\theta/4 - b_{-1}\theta/4 = \theta \cdot b/2 > 0$, since $b_i = b_{-i}$ and $b = b_0 - b_1$ is always positive (Economides 1993).

Lemma 2: $dp_i^*/dE(\overline{q_j}) = -\theta \cdot b_m/2$, for $i \neq j$, where $m = k - i$

Proof: From Equation [6], $dp_i^*/dE(\overline{q_j}) = \theta(b_m/2 - b_{m-1}/4 - b_{m+1}/4) = -\theta \cdot b_m/2$, because $4b_m = b_{m+1} + b_{m-1}, \forall\, m \neq 0$, by the properties of $\mathbf{A}^{-1}$.

Lemma 2 says that if the expected quality of vendor S_k, increases by ε, vendor S_i's equilibrium price would decrease by $\theta b_m \varepsilon/2$, where $m = k - i$ is the number of vendors between vendors k and i.

ii. The Information Disclosure Investment Stage

In the information disclosure subgame, vendors have chosen their product details and have received information about how their own uncertainty intervals will look if they decide to withhold product information. They expect that by withholding information, they may cause buyers to reevaluate the uncertainty intervals, taking into account the fact that vendors have withheld information, and finally they anticipate that in the pricing stage they will price according to Equations [5] and [6].

[Taste-related Information] We will be using the following Lemma (proof omitted for brevity):

Lemma 3: Vendors do not release product type information for any $c_d > 0$

The intuition is that a vendor's type disclosure which changes $E\left(\overline{d_i}\right)$ by some constant z, causes one neighbor in the type space to lower price by $z \cdot t \cdot b_{+1}$ (the vendor to which he is now perceived to be closer), while causing the neighbor to which he is perceived to be moving away from, to raise his price by $z \cdot t \cdot b_{-1}$. The net effect of these changes on the vendor's profit is zero minus the disclosure cost c_d. A similar result was obtained in (Markopoulos et al. 2010) in a model that also allows for vendors to charge buyers in order to provide them with the information that they would not release in the absence of such a payment.

Lemma 3 allows us to derive the distribution of $E(\overline{d_i})$, before horizontal uncertainty intervals realize prior to Stage 4. For uniform $f_{dj}(\cdot)$, $E(\overline{d_i})$ is simply the center of a vendor's horizontal uncertainty interval. Since d_{iA} can range from d_i to $d_i + \alpha_d$, the center of the uncertainty interval can range from $d_i - \alpha_d/2$ to $d_i + \alpha_d/2$. Further, since no vendor chooses to disclose type information, buyers do not receive any signal from vendors who do not disclose type. Thus:

Lemma 4: Before uncertainty intervals realize, $E(\overline{d_i})$ is a random variable $E(\overline{d_i}) = d_i + \varepsilon$, where ε is a random variable which is uniformly distributed with support $[-a_d/2, a_d/2]$. Thus, $dE(\overline{d_i}) = dd_i$

For c constant, we obtain the following properties for ε:

$$\int_{-a_d/2}^{a_d/2} \frac{\varepsilon}{\alpha_d} d\varepsilon = 0, \qquad \int_{-a_d/2}^{\alpha_d/2} c\frac{1}{\alpha_d} d\varepsilon = c, \qquad \int_{-a_d/2}^{\alpha_d/2} \varepsilon^2 \frac{1}{\alpha_d} d\varepsilon = \frac{{\alpha_d}^2}{12} \quad \textbf{[7]}$$

We will contrast this with quality information, where buyers do receive a signal from vendors who do not to disclose and use the signal to reduce their uncertainty about these buyers' quality.

[Quality Information] Using Equation [3] and Lemma 1, a vendor's profit (minus the required disclosure cost) is increasing in perceived quality: $\frac{d(\Pi_i^* - r_i)}{dE(\overline{q_i})} = \frac{dR_i^*}{dE(\overline{q_i})} - \frac{dC(q_i)}{dE(\overline{q_i})} = \frac{2p_i^*}{t} \cdot \frac{dp_i^*}{dE(\overline{q_i})} - 0 = \frac{p_i^* \cdot \theta \cdot b}{t} > 0$ (the quality production cost has already been incurred in Stage 2, so that now $dC(q_i)/dE(\overline{q_i}) = 0$). Further, buyers know that vendors have knowledge of their uncertainty intervals and disclosure of quality information entails a cost c_q. Thus, our model satisfies the assumptions of the classic analysis of costly quality disclosure (Verrecchia 1983) (Fishman and Hagerty 2003) so that quality information unravels above a threshold:

Lemma 5: Given seller S_i's quality uncertainty interval $[q_{iA,}q_{iB}]$, there exists a quality level $\widetilde{q_i} \in [q_{iA,}q_{iB}]$, so that iff $q_i > \widetilde{q_i} \Leftrightarrow q_i \in [\widetilde{q_i}, q_{iB}]$, S_i will disclose

If the seller does not disclose the buyers will reduce their expectation of the vendor's quality to:

$$\underline{q_i} = \int_{q_{iA}}^{\widetilde{q_i}} \frac{x f_{qi}(x)}{F_{qi}(\widetilde{q_i}) - F_{qi}(q_{iA})} dx = \int_{q_{iA}}^{\widetilde{q_i}} \frac{x f_{qi}(x)}{F_{qi}(\widetilde{q_i})} dx = \frac{q_{iA} + \widetilde{q_i}}{2} \quad \textbf{[8]}$$

$\widetilde{q_i}$ is such that if $\delta_i \equiv \widetilde{q_i} - \underline{q_i}$, then $R_i^*(\widetilde{q_i}) - c_q = R_i^*(\widetilde{q_i} - \delta_i)$, so that the revenue that a vendor with quality $\widetilde{q_i}$ gives up by withholding quality information, is offset by disclosure cost savings. In general $\widetilde{q_i}$ may not be unique. However, the uniform $f_{qi}(\cdot)$ is a log-concave function, so that, given q_{iA}, δ_i is increasing in $\widetilde{q_i}$ (Bagnoli and Bergstrom 2005), and thus $\widetilde{q_i}$ is unique, given $f_{qi}(\cdot)$ [5].

We can also define $Pr_i(q_i)$ to be the probability that vendor S_i will disclose, given quality q_i:

$$Pr_i(q_i) = Prob(q_i > \widetilde{q_i}) = 1 - 2\delta_i/\alpha_q \quad \textbf{[9]}$$

Before we are able to calculate the equilibrium value of δ_i, we must know the distribution of $E(\overline{q_i})$, before the uncertainty intervals realize. We can show that (proof omitted):

Lemma 6: Before uncertainty intervals realize, $E(\overline{q_i})$ is a random variable $E(\overline{q_i}) = q_i + \varphi$, with φ a random variable with support $[-\delta_i, \delta_i]$ and PDF f'_{qi} given by: $Pr_i(q_i) \cdot \frac{1}{2\delta_i} + (1 - Pr_i(q_i)) \cdot \delta(\varphi)$, where $\delta(\varphi)$ is Dirac's delta function.

For c constant, and by using Equation [9], we obtain the following properties for f'_{qi}:

[5] See (Cheong and Kim 2004). *f* is log-concave if *ln(f)* is concave in its support (e.g., uniform, normal, etc.)

$$\int_{-\delta_i}^{\delta_i} \varphi \cdot f'_{qi}(\varphi) \cdot d\varphi = 0, \quad \int_{-\delta_i}^{\delta_i} c \cdot f'_{qi}(\varphi) \cdot d\varphi = c, \quad \int_{-\delta_i}^{\delta_i} \varphi^2 \cdot f'_{qi}(\varphi) \cdot d\varphi = \frac{\alpha_q{}^2\left(1-Pr_i(q_i)\right)^3}{12} \quad \textbf{[10]}$$

In equilibrium, all firms will choose their quality disclosure strategy according to Lemma 5 and vendor S_i will choose his optimal quality disclosure threshold $\tilde{q_i}$, consistent with every other vendor S_j optimally choosing quality disclosure threshold $\tilde{q_j}$. We can now show that $\delta_i \equiv \tilde{q_i} - \underline{q_i}$ is given as a function of q_i by:

$$\delta_i = min\left[\frac{2}{\theta \cdot b}\left(p_i^*(q_i|\forall j \neq i: E(\overline{q_j}) = q_j) - \sqrt{p_i^*(q_i|\forall j \neq i: E(\overline{q_j}) = q_j)^2 - t \cdot c_q}\right), \alpha_q/2\ \right] \quad \textbf{[11]}$$

Buyers discount non-disclosing products by $\alpha_q/2 - \delta_i > 0$, since buyers update their expectation for the product's expected quality from $q_{iA} + \alpha_q/2$ to $q_{iA} + \delta_i$, as δ_i was defined to be $\delta_i \equiv \tilde{q_i} - \underline{q_i}$.

Note that vendor S_i's equilibrium price in Equation [11], is the price that vendor S_i would have chosen if for all other vendors $E(\overline{q_j})$ exactly matched q_j. In other words, the formula says that a vendor who must choose his quality disclosure threshold $\tilde{q_i}$, optimizes by assuming that for every competitor S_j, $E(\overline{q_j})$ will neither overestimate nor underestimate the competitor's true quality q_j.

For simplicity, the remaining of the article will somewhat abuse the notation and use $p_i^*(q_i)$ to mean: $p_i^*(E(\overline{q_i}) = q_i|E(\overline{q_{j\neq i}}) = q_j)$.

We can now use Equation [9] to immediately derive the exact form of $Pr_i(q_i)$ as well as the quality investment cost, beyond which no vendor would wish to invest in quality disclosure:

Lemma 7: $Pr_i(q_i) = max\left[0,\ \ 1 - \frac{4}{\theta \cdot b \cdot \alpha_q}\left(p_i^*(q_i) - \sqrt{p_i^*(q_i)^2 - t \cdot c_q}\right)\right]$

Lemma 8: $Pr_i(q_i) = 0, when\ c_q > \frac{\alpha_q \cdot \theta \cdot b}{2t}\left(\left(p_i^*(q_i)\right) - \frac{\alpha_q \cdot \theta \cdot b}{8}\right)$

To summarize, vendors will disclose quality information if and only if their quality exceeds a threshold within their quality uncertainty interval and the probability of disclosure can be zero, for high enough c_q. In general, it may happen that a lower quality vendor exceeds this quality threshold inside her own uncertainty interval, but that a higher quality vendor does not.

Proof of Proposition 1: The proposition can be proven either by starting from Equation [11]. δ_i decreases in equilibrium price p_i^* : $d\delta_i/dp_i^* = \cdots = \frac{2}{\theta b}\left(1 - p_i^*/\sqrt{p_i^{*2} - t \cdot c_q}\right) < 0$. Thus, $\frac{d\delta_i}{dE(\overline{q_i})} = \left(\frac{d\delta_i}{dp_i^*}\right) \cdot \left(\frac{dp_i^*}{dE(\overline{q_i})}\right) = \left(\frac{d\delta_i}{dp_i^*}\right) \cdot \theta \cdot \frac{b}{2} < 0$. Further, given q_{iA}, δ_i is 1-1 with $\tilde{q_i}$ and it is also true that $dE(\overline{q_i})/dq_i > 0$. Thus we obtain $d\delta_i/dE(\overline{q_i}) < 0 \Leftrightarrow d(\tilde{q_i} - q_{iA})/dE(\overline{q_i}) < 0 \Leftrightarrow d(\tilde{q_i} - q_{iA})/dq_i < 0$. Fixing q_{iA} also fixes q_{iB}, thus $d(q_{iB} - \tilde{q_i})/dq_i > 0$, so that $Prob(q_i > \tilde{q_i})$ is increasing in q_i. This proves Proposition 1.

iii. The Quality and Type Choice Stages

Since firms choose quality and type before they learn competitors' choices, they are, in effect, choosing quality and type simultaneously. Firms anticipate that in information disclosure stage they will not disclose type information, and that the probability that they will disclose quality information is increasing with their quality choice at the present stage. Firms further anticipate that in the final game stage, prices will follow the non-cooperative equilibrium given in vector form by Equation [5].

For equilibrium derivation, only the conditional expected profit of Firm S_i is required, i.e., the expected profit that takes competitor choices as given. From Lemma 1 and Equations [3] and [10] conditional expected profit is:

$$E(\Pi(q_i)) = E\left(\frac{p_i^*(E(\overline{q_i}))^2}{t} - \frac{k \cdot q_i{}^2}{2} - c_q Pr_i(q_i)\right) = \int_{-\delta_i}^{\delta_i}\left(\frac{p_i^*(q_i+\varphi)^2}{t} - \frac{k \cdot q_i{}^2}{2} - c_q Pr_i(q_i)\right) f'_{qi}(\varphi) d(\varphi) =$$

$$\int_{-\delta_i}^{\delta_i} \frac{\left(p_i^*(q_i) + \frac{\theta \cdot b \cdot \varphi}{2}\right)^2}{t} f'_{qi}(\varphi) d(\varphi) - \frac{k \cdot q_i{}^2}{2} - c_q Pr_i(q_i) = \frac{p_i^*(q_i)^2}{t} + 0 + \int_{-\delta_i}^{\delta_i} \frac{(\theta \cdot b \cdot \varphi)^2}{4t} \cdot f'_{qi}(\varphi) d(\varphi) - \frac{k \cdot q_i{}^2}{2} - c_q \cdot Pr_i(q_i)$$

$$\Leftrightarrow \cdots \Leftrightarrow E(\Pi(q_i)) = \frac{p_i^*(q_i)^2}{t} - \frac{k \cdot q_i{}^2}{2} - c_q \cdot Pr_i(q_i) + \frac{\theta^2 b^2 \alpha_q{}^2 \left(1 - Pr_i(q_i)\right)^3}{48 \cdot t} \qquad \textbf{[12]}$$

Since a firm simultaneously optimizes on quality and type, $\partial q_i/\partial d_i = 0$. Equation [6] yields $\frac{\partial p_i}{\partial d_i} = \frac{\partial p_i}{\partial E(\overline{d_i})} \cdot \frac{\partial E(\overline{d_i})}{\partial d_i} = t \cdot \frac{(b_{-1} - b_{+1})}{4} \cdot 1 = 0$. This is because $\partial e_{i+j}(\mathbf{q}, \mathbf{d}) / \partial E(\overline{d_i}) = 0$ for $j \neq -1, +1$, $b_j \left(\partial e_{i+j}(\mathbf{q}, \mathbf{d}) / \partial E(\overline{d_i})\right) = -tb_{+1}/4$, for $j = +1$, $b_j \left(\partial e_{i+j}(\mathbf{q}, \mathbf{d}) / \partial E(\overline{d_i})\right) = -tb_{-1}$ for $j = -1$, $b_{+1} = b_{-1}$ because $\mathbf{A^{-1}}$ is symmetric circulant, and finally, from Lemma 4, $\frac{\partial E(\overline{d_i})}{\partial d_i} = 1$. Using $\frac{\partial p_i}{\partial d_i} = 0$ and $\frac{\partial q_i}{\partial d_i} = 0$, Equation [12] yields $\partial E(\Pi(q_i))/\partial d_i = 0$. Thus, if there exists a market equilibrium, then there also exists an equilibrium with symmetric types, with $d_j - d_{j-1} = 1/N, \forall j$.

We will also make use of the following two Lemmata (proof omitted):

Lemma 9: $q_i^* = argmax_{q_i} \Pi\left(q_i \middle| \forall j \neq i: E(\overline{q_j}) = q_j\right)$

Lemma 10: $q_i^* = argmax_{q_i} \Pi\left(d_i \middle| \forall j \neq i: E(\overline{d_j}) = d_j\right)$

What these two Lemmata say is that a vendor's optimal quality is the same as the quality that the vendor would have chosen, if all of his competitors quality and type choices were to become exactly known to the consumers, or alternatively, that a vendor should neither overestimate nor underestimate his competitors' expected qualities, compared to their actual choices.

Using Lemma 9 and Lemma 10 and working with the actual choices of competitors d_j and q_j, instead of the random variables $\overline{d_j}$ and $\overline{q_j}$, and assuming that initially all vendors have chosen symmetric types: $d_j - d_{j-1} = \frac{1}{N}, \forall j$ and that all vendors except vendor S_i have chosen qualities $q_j = q, \forall j \neq i$, then from Equation [6],

$$p_i^*\left(q_i \middle| \forall j \neq i: E(\overline{q_j}) = q, \forall m: E(\overline{d_m}) - E(\overline{d_{m-1}}) = \tfrac{1}{N}\right) = \sum_{j=-N/2}^{N/2}\left(b_j \tfrac{t}{2N}\right) + \tfrac{b \cdot \theta}{2}(q_i - q) =$$

$= \frac{t}{2N}\left(\sum_{j=-N/2}^{N/2} b_j\right) + \frac{b \cdot \theta}{2}(q_i - q) = \frac{t}{N} + \frac{b \cdot \theta}{2}(q_i - q)$, because the sum of elements of any row of $\mathbf{A^{-1}}$ equals 2. Vendor S_i, optimizes quality when $\partial E(\Pi(q_i))/\partial q_i = 0 \Leftrightarrow$

$$q_i^* = \frac{b \cdot \theta \cdot p_i{}^*}{k \cdot t} - \theta \cdot b \cdot \frac{16 \cdot c_q \cdot t + b^2 \cdot \theta^2 \cdot \alpha_q{}^2 \cdot \left(1 - Pr_i(q_i)\right)^2}{32 \cdot k \cdot t} \cdot \left(\frac{dPr_i(q_i)}{q_i}\bigg|_{q_i = q_i^*}\right) \qquad \textbf{[13]}$$

We can show that Equation [13] leads to (proof omitted):

Lemma 11: There exists a symmetric equilibrium in qualities and types, where vendors place their products symmetrically in the type space $d_i - d_{i-1} = 1/N$, and:

$$q^* = \begin{cases} \dfrac{\theta \cdot b}{k \cdot N} & , c_q > c_q{}' \\[2ex] \dfrac{\theta \cdot b}{k \cdot N} - \left(\dfrac{t}{N}\right)^2 \dfrac{8\left(\frac{t}{N}\right)^2 - 4t \cdot c_q - 8\Gamma}{\alpha_q . k \cdot t \cdot \Gamma} & , c_q < c_q{}' \end{cases}$$

where $\Gamma = \frac{t}{N}\sqrt{\left(\frac{t}{N}\right)^2 - t \cdot c_q}$ and $c_q' = \frac{\alpha_q \cdot \theta \cdot b}{2t}\left(\frac{t}{N} - \frac{\alpha_q \cdot \theta \cdot b}{8}\right)$

Proof of Proposition 2: follows directly from Lemma 11, by observing that $\alpha_q = 0$ implies $c_q' = 0$. In general, we do not need the symmetric equilibrium in qualities to derive Proposition 2. We are able to show that any type $\mathbf{d}_{init} = [d_1^*, d_2^* \dots d_N^*]$ gives rise to a unique type-quality equilibrium, that is the solution to the system $\forall i: q_i^* = \frac{b \cdot \theta \cdot p_i(\mathbf{d}_{init}, \mathbf{q}_{init})}{k \cdot t} - \theta \cdot b \frac{16 c_q \cdot t + b^2 \theta^2 \alpha_q{}^2 \left(1 - Pr(q_i^*)\right)^2}{32 k \cdot t}\left(\frac{dPr_i(q_i)}{q_i}\bigg|_{q_i = q_i^*}\right)$, where $p_i(\mathbf{d}_{init}, \mathbf{q}_{init})$ and $Pr(q_i^*)$ are increasing functions of q_i^* that also depend $\mathbf{d}_{init}$ and on all other $q_j^*, j \neq i$. It is then easy to show that equilibrium quality can only increase if we set $a_q = 0$.

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