Information Leakage in Supply Chains

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Abstract

Information sharing within a supply chain has numerous benefits. However, in the past decade, several works have pointed out using game-theoretic models that: (i) a supply chain entity may not have an incentive to share information for fear of exploitation by the party (e.g. manufacturer) with whom they share information as well as leakage of information to their competitors, (ii) the negative effects of information leakage can be mitigated by using appropriate contracts between supply chain entities. This chapter reviews this literature and provides a framework for classifying it. The most common supply chain structure analyzed in these works comprises of a manufacturer supplying a set of retailers who share demand information with the manufacturer which may be leaked to other retailers. The literature has shown that while vertical information sharing with the manufacturer always has negative effects, the horizontal leakage of information, either direct or indirect, to other retailers can have positive or negative effects and the strength of these effects depends on a number of factors. These include whether the competition among retailers is on price or quantity, whether their products are substitutes or complements, whether information sharing arrangements are made before or after private information is revealed and the level of accuracy of private information among different entities. To incentivize truthful information sharing despite the potential for leakage and its negative effects, the literature has come up with a variety of solutions: side payments by manufacturers to retailers, different wholesale prices charged to different retailers, revenue sharing contracts and market-based contracts. In addition, retailers can enter into a binding confidentiality agreement to prevent leakage. Some of these solutions can coordinate the supply chain and sometimes benefit all the entities, including ones that do not have private information. While anecdotal evidence from industry suggests that firms primarily fear direct leakage of information to their competitors, two important insights from the academic literature are: (i) indirect leakage of information can have as significant an effect on the incentives to share information as direct leakage, (ii) information leakage to competitors can sometimes have positive effects.

1 Introduction

The information revolution has spawned a dramatic growth in the amount of information available to firms. The benefits of information sharing within a supply chain have been well-documented in both the trade and academic literature over the past two decades. The emergence of initiatives such as Vendor Managed Inventory (VMI), Collaborative Planning, Forecasting and Replenishment (CPFR) has accelerated the trend towards sharing information to take advantage of these benefits. Lee and Whang (2000) provide a nice summary of the benefits of information sharing based on industry practices. However, they also point out that "information sharing faces several hurdles" including loss of *information rent* and *leakage of information* to unintended parties in the supply chain. Subsequently, several works have pointed out using formal models that a supply chain entity may not have an incentive to share information for fear of exploitation by the party (e.g. manufacturer) with whom they share information as well as leakage of information to their competitors. An example from Anand and Goyal (2009) illustrates the challenges faced in sharing information given the possibility of information leakage.

Newbury Comics is a small, trendy chain in the Northeast that sells music records. This retail chain is seen as a trendsetting retailer that is able to identify early which artists are likely to break out and which records and type of music are likely to be hot-sellers. SoundScan is a company that tracks music records sold by a vast majority of the retailers in the US, including small ones like Newbury as well as larger ones like Best Buy, and passes along this information to upstream record labels such as Sony as well as middlemen such as Handleman Inc., who manage the shelf inventories of large retailers such as Best Buy and Wal-Mart. Record labels such as Sony found the sharing of information by the retailers valuable, especially given the hit-and-miss nature of this market and provided promotional and co-advertising support to retailers to share this information. However, over time, Newbury realized that it was losing its competitive edge in the market because the valuable information it was sharing with SoundScan was in turn being used by Handleman to make inventory planning and replenishment decisions at retailers such as Wal-Mart. So, it stopped sharing information.

This example raises a number of questions that are the focus of this chapter. How do the record labels benefit from the retailers sharing information with SoundScan? Why do they provide incentives such as promotion and advertising support to the retailers to share information? What is the loss to Newbury from sharing information? What can the record labels do to incentivize Newbury to share information, given its genuine concern about loss of market advantage?

There are other examples provided in Anand and Goyal (2009), Gal-Or et al. (2008) and Kong et al. (2013) on the leakage of information in supply chains as well as the reluctance to share information due to the threat of information leakage. There are several forces that result in the leakage of information in a supply chain, whether intentionally or otherwise. First, vertical information is shared by a retailer with a supplier or an intermediary (such as SoundScan in the Newbury Comics case) who aggregates information and shares it with other retailers. Second, the emergence of category management in the retail industry has resulted in information being shared by retailers with a leading manufacturer who manages a category, called the "category captain". In practice, a leading manufacturer serves as a category captain for many retailers that are competing for the same consumers (Kurtulus and Toktay 2008). While retailers find the benefits of category management and category captainship attractive, this can result in valuable information being shared by the category captain with competing retailers. As Kurtulus and Toktay (2008) point out, "the trade-off that retailers face is the benefit from category captainship versus the potential problems and loss of competitiveness that could arise from information leakage." Third, initiatives such as VMI and CPFR have accelerated the sharing of information between manufacturers and retailers as well as between suppliers and a manufacturer who uses their inputs. In turn, this has increased the likelihood of the shared information being leaked to unintended recipients in a supply chain. The leakage of information may occur by accident or due to deliberate efforts to obtain proprietary information either by competitors or third parties. For example, hackers recently managed to get into the computer systems at Foxconn, a major supplier of consumer electronics to large corporations such as Apple and HP, and post information about their client purchases (Mello 2012). Finally, the information may not be leaked directly but observable actions based on that information taken by an entity in the supply chain may unwittingly reveal the confidential information.

The fear and negative effects of information leakage may result in firms not sharing information and reaping the corresponding benefits. Ron Ireland, who helped develop CPFR processes at Wal-Mart points out that while Wal-Mart was willing to share its forecasts and POS data with vendors, the sales teams within those vendor organizations were scared to share it with their own corporate offices for fear that information may leak to third parties and they would get into trouble with Wal-Mart (Douglas 2004). Adewole (2005) points out that retailers in the UK clothing industry are "reluctant to share information with suppliers, recognizing that those suppliers might also be supplying competitors and could wittingly or unwittingly divulge sensitive information."

The articles reviewed in this chapter provide insights into the issues raised above using game-theoretic models. In particular, the focus of this chapter is on information leakage. We would like to clarify some terms upfront. By the definition given in the Oxford Dictionaries, "leakage" refers to the "deliberate disclosure of confidential information." We use the term "leakage" in a broader sense in that it can be both intentional (deliberate) and unintentional because it is difficult to verify a decision maker's intentions. We also allow leakage to be direct or indirect. An act of "direct leakage" means that the receiver of the confidential information passes that information directly to a third party without the consent of the sender of that information. An act of "indirect leakage" means that a third party can infer (perhaps partially) the sender's information from the receiver's public actions indirectly. As a common practice, direct leakage can be prevented or deterred by a binding confidentiality agreement between the sender and the receiver. However, such an agreement is often ineffective in preventing indirect leakage. In this

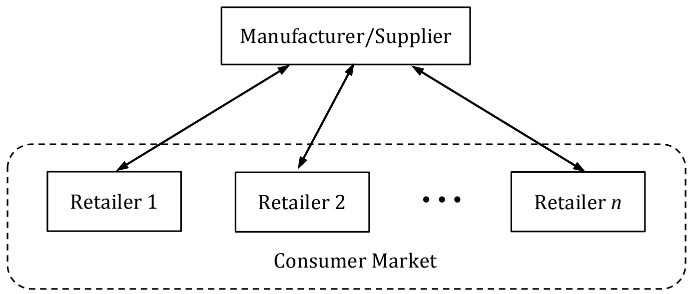

Figure 1: A common supply chain structure with multiple retailers.

article, we use "confidentiality" and "no direct leakage" interchangeably. We also treat "degree of confidentiality" and "degree of nonleakage" roughly the same.

1.1 Basic Framework

A typical model of a supply chain with (vertical) information sharing and (horizontal) information leakage is illustrated in Figure 1, first introduced by Li (2002). The supply chain consists of a common manufacturer or supplier ("she") at the upstream, denoted by M, and multiple retailers ("he") at the downstream, labeled by $N = \{1, 2, \cdots, n\}$. The retailers compete in a common consumer market based on either quantity or price, i.e., engaging in a Cournot or Bertrand competition.

In the case of Cournot competition, the retail prices are determined from sales quantities as follows:

$$p_i = a + \theta - q_i - \beta \sum_{j \neq i} q_j, \quad \forall i \in N, \tag{1}$$

where p_i and q_i are the price and quantity of retailer i's product. The intercept $a + \theta$ represents the market condition or potential, where θ is a random variable with zero mean and variance σ^2. The parameter β (with $|\beta| \leq 1$) captures the degree of substitution or competition. When $\beta = 1$, the retailers' products are perfect substitutes and the competition is most intensive, in which case the retail prices are identical and can be denoted by p. When $0 < \beta < 1$, the products are imperfect substitutes and the competition is imperfect as well. The products are independent when $\beta = 0$ and complements when $-1 \leq \beta < 0$.

In the case of Bertrand competition, the sales quantities are determined from retailer prices:

$$q_i = a + \theta - (1 + \gamma)p_i + \frac{\gamma}{n-1} \sum_{j \neq i} p_j, \quad \forall i \in N. \tag{2}$$

The products are imperfect substitutes when $\gamma > 0$ (with the degree of substitution increasing in γ), independent when $\gamma = 0$, and imperfect complements when $-\frac{1}{2} < \gamma < 0$ (which satisfies $|1 + \gamma| > |\gamma|$).

It is often assumed that each retailer i observes a private signal Y_i about the uncertain

θ. The signals have the following properties: (1) $E(Y_i|\theta) = \theta$, $\forall i \in N$; (2) $E(\theta|Y_1, \cdots, Y_n) = \alpha_0 + \sum_{i \in N} \alpha_i Y_i$, for some constants α_i; (3) Y_i, $i \in N$, are independent and identically distributed, conditional on θ.[1] These assumptions imply (Lemma 1, Li 1985):

$$E(\theta|Y_j, j \in K) = E(Y_i|Y_j, j \in K) = \frac{1}{k+s} \sum_{j \in K} Y_j, \quad i \in N \backslash K, \tag{3}$$

where $K \subset N$ is the set of retailers participating in information sharing, $k = |K|$, and $s = E(Var(Y_i|\theta))/\sigma^2$ is a measure of signal errors. This result means that $\sum_{j \in K} Y_j$ is a sufficient statistic of $(Y_j)_{j \in K}$ for the purpose of estimating θ and unknown signals.

There are two basic classes of models in this body of literature. In one class, the members of the supply chain determine how the private information will be transmitted in the supply chain prior to the arrival of that information and their operational activities, which is pioneered by Li (2002) and will be called the "ex-ante information sharing arrangement." In the other class, the members do not resort to any formal agreement in advance and the flow of private information in the supply chain is resolved after the information is available and through the interaction of the parties. This setting is exemplified by the work of Anand and Goyal (2009) and will be called the "ex-post information sharing arrangement."

Table 1 lists the collection of papers that have addressed the issue of information leakage in a supply chain. The second column in the table identifies the nature of information sharing arrangement: whether it is ex-ante or ex-post. The third column identifies whether information is shared directly or indirectly or both. It is interesting to note that all the works in the literature on information leakage have considered a supply chain structure where the competition is at the downstream end (i.e., a manufacturer supplies multiple retailers) or two supply chains, each with a manufacturer and retailer, compete with each other. At the retail level, the competition could be based on quantity (Cournot) or price (Bertrand) and the fourth column in Table 1 identifies this aspect of the models. The fifth column identifies whether the model has 2 or more retailers or if there are two supply chains competing with each other. The sixth column examines whether the products are substitutes or complements. Most papers except Zhang (2002) focus on perfect or imperfect substitutes. Finally, the last column identifies some unique aspects of the models considered in a paper. For example, most of the papers assume a wholesale price contract between the manufacturer and the retailers but a few papers have considered other types of contracts or mechanisms, e.g. revenue sharing, side payments, market-based contracts, and auction.

[1] Some prior-posterior conjugate distributions, e.g., normal-normal, gamma-Poisson, and beta-binomial, satisfy these assumptions. However, as pointed out by Zhang (2008), assumption (2) imposes some restrictions on how much about θ can be learned from these signals.

Table 1: Publication Classification

Publication or Working Paper	Information: Sharing Decision	Information: Leakage	Retail Competition	Number of retailers	Type of Product	Other
Li (2002)	Ex-ante	Direct	Cournot	$N \geq 2$	Perfect substitutes	Cost information, Side payments
Zhang (2002)	Ex-ante	Direct	Cournot, Bertrand	2	Imperfect substitutes, complements	Side payments
Li & Zhang (2008)	Ex-ante	Direct, Indirect	Bertrand	$N \geq 2$	Imperfect substitutes	
Gal-Or et al. (2008)	Ex-ante	Direct, Indirect	Bertrand	2	Imperfect substitutes	M has private information
Anand & Goyal (2009)	Ex-post	Direct	Cournot	2	Perfect substitutes	Information aquisition
Chen & Vulcano (2009)	Ex-ante	Direct	Cournot	2	Perfect substitutes	Auction pricing
Shin & Tunca (2010)	Ex-ante	Indirect	Cournot, Bertrand	$N \geq 2$	Perfect substitutes	Two-part tariff, Market-based contract
Jain et al. (2011)	Ex-ante	Direct	Cournot	$N \geq 2$	Perfect, imperfect substitutes	Different wholesale prices
Ha et al. (2011)	Ex-ante	Minimum	Cournot, Bertrand	Two SCs with one M one R	Imperfect substitutes	Competing SCs
Qian et al. (2012)	Ex-ante	Direct	Cournot	$N \geq 2$	Perfect substitutes	M has limited capacity
Shamir (2012)	Ex-ante	Direct	Bertrand	$N \geq 2$	Imperfect substitutes	Mechanism design
Kong et al. (2013)	Ex-post	Direct	Cournot	2	Perfect substitutes	Revenue sharing
Jain & Sohoni (2015)	Ex-ante	Direct, Indirect	Cournot	2	Imperfect substitutes	Different wholesale prices
Shamir (2015)	Ex-post	Direct, Indirect	Bertrand	$N \geq 2$	Perfect substitutes	Infinite horizon
Shamir & Shin (2015)	Ex-post	Direct	Cournot	Two SCs, with one M one R	Perfect substitutes	Competing SCs

Table 2: **Information Known or Disclosed to Different Parties**

Scenario	Manufacturer	Participating retailer $i \in K$	Non-participating retailer $i \notin K$
S1	$\sum_{j\in K} Y_j$	Y_i and $\sum_{j\in K} Y_j$	Y_i and $\sum_{j\in K} Y_j$
S2	$\sum_{j\in K} Y_j$	Y_i and $\sum_{j\in K} Y_j$	Y_i and $w(\sum_{j\in K} Y_j)$
S3	$\sum_{j\in K} Y_j$	Y_i and $w(\sum_{j\in K} Y_j)$	Y_i and $w(\sum_{j\in K} Y_j)$

2 Ex-Ante Information Sharing Arrangement

A stream of papers share the basic model setup of Li (2002). The manufacturer and retailers' marginal costs are normalized to zero, without loss of generality. Events take place in the following order:

(1) The manufacturer (M) and retailers make an information sharing arrangement, i.e., deciding the set K of retailers who will share their information with the manufacturer;

(2) Each retailer i observes signal Y_i and, if $i \in K$, shares it with M;

(3) M sets the wholesale price w;

(4) Each retailer i chooses an order quantity q_i (under Cournot competition) or retail price p_i (under Bertrand competition);

(5) M delivers the products and the market is cleared.

Li and Zhang (2008) propose three scenarios of information sharing and leakage, or degrees of confidentiality, as summarized in Table 2, which offers a useful perspective to organize the existing literature.

In scenario (S1), M leaks the information collected from *participating* retailers (those in K) to all retailers directly. In other words, there is no confidentiality. In (S2), M only leaks the collected information to the participating retailers directly, which corresponds to partial confidentiality. In (S3), M does not leak any information to any retailer directly, i.e., participating retailers' information is kept by M with full confidentiality. However, all retailers can infer $\sum_{j\in K} Y_j$ from the wholesale price w indirectly (it is commonly assumed that w is strictly increasing in $\sum_{j\in K} Y_j$ in the equilibrium). Information inferred indirectly is less reliable (and hence less valuable) than that acquired directly, as the former is subject to manipulation and incentive concerns. Thus, when $\sum_{j\in K} Y_j$ can be obtained directly, the wholesale price $w(\sum_{j\in K} Y_j)$ only plays the traditional role of price setting, without the role of signaling.

Note that the scenarios in Table 2 require less information than the ones defined in Li and Zhang (2008): the full information $(Y_j)_{j\in K}$ is replaced by the aggregate information $\sum_{j\in K} Y_j$, because the latter is a sufficient statistic of the former as discussed earlier. Although the two sets of scenarios are mathematically equivalent, the current ones are considerably easier to implement in practice. It has been shown that aggregate information can be shared through secured protocols without revealing private information held individually (Deshpande et al. 2010).

2.1 Li (2002) & Zhang (2002)

Li (2002) investigates the full-leakage scenario (S1) under Cournot competition with perfect substitutes. Using backward induction, the paper shows the following negative result (Proposition 4): Given any information sharing arrangement $K \subset N$, the manufacturer is better off by acquiring information from more retailers, but each retailer is worse off by sharing information with the manufacturer; thus, no information sharing, or $K = \emptyset$, is the unique equilibrium.

This result is driven by two effects of information sharing. The direct effect (*loss of information rent*) is that more information allows the manufacturer to extract more surplus from a retailer through the choice of wholesale price, as evident from the equilibrium wholesale price: $w^*((Y_j)_{j\in K}) = \frac{a}{2} + \frac{1}{2(k+s)} \sum_{j\in K} Y_j$.[2] The indirect effect of information sharing (*loss of competitive advantage*) refers to the leakage of a participating retailer's demand information to his competitors and the resulting information disadvantage. The expressions for the sales quantities are given by (Proposition 1):

$$q_i^*(Y_i, w^*) = \frac{1}{n+1}\left(a - w^* + A_1^k \sum_{j\in K} Y_j\right), \quad i \in K, \tag{4}$$

$$q_i^*(Y_i, w^*) = \frac{1}{n+1}\left(a - w^* + B_1^k \sum_{j\in K} Y_j + B_2^k Y_i\right), \quad i \in N\backslash K, \tag{5}$$

for some positive constants A_1^k, B_1^k, and B_2^k. Thus, a non-participating retailer exploits both the leaked information $\sum_{j\in K} Y_j$ and his private information Y_i, while a participating one can only utilize $\sum_{j\in K} Y_j$.

Because of the misaligned incentives between the manufacturer and the retailers, it may be beneficial for the manufacturer to buy information from the retailers. Stage (1) of the sequence of events is modified as follows: M promises each retailer a fee δ if he will share his information later, and each retailer decides whether to accept the payment and commit to information sharing. The paper shows that (Proposition 5) in the augmented game, there are only two possible equilibria, complete information sharing ($K = N$) and no information sharing ($K = \emptyset$), and the former Pareto dominates the latter if and only if $s \leq (n-2)(n+1)/2$. It also shows that complete information sharing hurts both the social benefits and consumer surplus (Proposition 7). Thus, information sharing should be discouraged from the standpoint of a social planner.

Zhang (2002) extends the main finding of Li (2002) to more general types of competition. The

[2] The paper shows that the manufacturer cannot gain from charging different w's to participating and non-participating retailers (if the wholesale price is determined after information sharing).

paper focuses on a supply chain with one manufacturer and two retailers who engage in either Cournot or Bertrand competition with imperfect substitutes or complements. It investigates the full-leakage scenario (S1) in Li (2002) and shows the following (Proposition 2): The manufacturer is always better off by acquiring demand information from more retailers; Each retailer is always worse off by disclosing his private information to the manufacturer; Therefore, no information sharing is the unique equilibrium.

As in Li (2002), information sharing has both direct (loss of information rent) and indirect (leakage) effects. When the products are substitutes (complements) under Cournot (Bertrand) competition, both effects are negative for a retailer. When the products are complements (substitutes) under Cournot (Bertrand) competition, the leakage effect is positive, but not strong enough to overcome the negative direct effect.

The paper further shows that the manufacturer may be able to induce information sharing by a side payment, which is easier to achieve when the products are closer to perfect complements (substitutes) in a Cournot (Bertrand) competition or the demand signals are statistically less accurate (s above a threshold).

2.2 Li and Zhang (2008)

This paper studies all three leakage scenarios, (S1), (S2), and (S3), under Bertrand competition with imperfect substitutes. The main differences among the three scenarios manifest themselves in the equilibrium retail prices. Let $r_i = p_i - w$ denote the margin of retailer i. In each scenario $S \in \{S1, S2, S3\}$, in the equilibrium, r_i^* are given by:

$$r_i^*(w) = \frac{1}{2+\gamma}[a - w + A_k \theta_P^S + (1 - A_k)\theta_N^S], \quad i \in K, \tag{6}$$

$$r_i^*(w) = \frac{1}{2+\gamma}[a - w + B_k Y_i + (1 - B_k)\theta_N^S], \quad i \notin K, \tag{7}$$

for some positive constants A_k and B_k. In the expressions, θ_P^S is the estimate of θ available to a participating retailer and θ_N^S is that to a nonparticipating retailer in scenario S. By the definition of the scenarios, we have: (1) $\theta_P^{S1} = \theta_N^{S1} = E(\theta | \sum_{j \in K} Y_j)$; (2) $\theta_P^{S2} = E(\theta | \sum_{j\in K} Y_j)$, $\theta_N^{S2} = g(w)$; and (3) $\theta_P^{S3} = \theta_N^{S3} = g(w)$, with the special case that $\theta_P^{S3} = E(\theta | Y_i)$ when $K = \{i\}$. The function $g(w)$ represents the estimation $E(\theta | \sum_{j\in K} \widetilde{Y}_j)$ where $\sum_{j \in K} \widetilde{Y}_j$ is inferred from $w(\sum_{j\in K} Y_j)$ (assuming a separating equilibrium). In scenario (S1), the wholesale price w is a pure price instrument for the manufacturer, while in scenarios (S2) and (S3), it also serves as a signaling device.

In the full-leakage scenario (S1), the paper confirms the results of Li (2002) and Zhang (2002), under oligopoly Bertrand competition. That is, information sharing benefits M but harms the retailers and, therefore, no information sharing is the unique equilibrium.

In the nonleakage scenario (S3), the following results are found (Propositions 3, 4, 7 & 8): When retail competition is intense (γ large enough), the only possible equilibria are complete information sharing ($K = N$) and no information sharing ($K = \emptyset$); The former can be induced voluntarily if (in addition) the demand information is less accurate (s large enough) or through a side payment from M to the retailers; In any case, complete information sharing Pareto-dominates no information sharing; Under complete information sharing, the supply chain is coordinated, and no retailer will misreport his signal if all other retailers do it truthfully.

These positive results stem from the weakened direct effect of information sharing (double marginalization) in scenario (S3). An increase (or decrease) of w would signal higher (or lower) demand and induce the retailers to raise (or reduce) their margins, which would dampen (or boost) the sales quantities as well as the manufacturer's profit. This change of price elasticity motivates the manufacturer to set a lower wholesale price in (S3) than in (S1). In short, the signaling role of the wholesale price under Bertrand competition alleviates the double marginalization in the supply chain, which benefits the retailers and the supply chain but hurts the manufacturer. This argument does not hold under Cournot competition with imperfect substitutes, because the signaling role of w encourages the increase of w as it would induce the retailers to increase order quantities which in turn benefits the manufacturer. That would only aggravate the double marginalization in the supply chain.

Comparing the scenarios, the paper shows that given the set of participating retailers K, a higher degree of confidentiality results in a lower equilibrium wholesale price, which harms the manufacturer and benefits all retailers (Propositions 5 & 6). Thus, the manufacturer prefers full leakage, the scenario (S1), and the retailers prefer full confidentiality, (S3). However, under (S1), the only equilibrium outcome is no information sharing ($K = \emptyset$), which from the manufacturer's perspective is worse than any arrangement $K \subset N$ under (S3). Therefore, the manufacturer and retailers should try to realize (S3) through a binding confidentiality agreement.

2.3 Jain, Seshadri and Sohoni (2011)

This paper tries to fill a gap left by Li (2002), Zhang (2002), and Li and Zhang (2008). It first shows or confirms the following negative results under Cournot competition (and a single wholesale price): no information sharing is the unique equilibrium in scenarios (S1) and (S3); in scenario (S2), no information sharing is always an equilibrium, while full information sharing is an equilibrium only for a special range of s and σ; furthermore, truth-telling by all retailers is not an equilibrium.

The paper then demonstrates that by charging differential wholesale prices, full information sharing can be achieved. The first stage in the sequence of events is modified to:

(1) M announces the pricing scheme $\{w_i\}_{i \in N}$, and each retailer decides whether to participate in information sharing, which defines the set $K \subset N$.

The paper focuses on affine pricing schemes of the form: $w_i^k = A_1^k + B_1^k \sum_{j \in K} Y_j - D^k Y_i$, $i \in K$, or $A_2^k + B_2^k \sum_{j \in K} Y_j$, $i \in N \backslash K$, for constants A_1^k, B_1^k, A_2^k, B_2^k, and D^k. The model assumes that the aggregate information $\sum_{j \in K} Y_j$ is publicly verifiable, which is in effect scenario (S1). The signal Y_i in the expression of w_i^k for $i \in K$ is reported by retailer i. Thus, the wholesale price w_i^k plays the role of screening a participating retailer's information. It is shown that (Proposition 2): The optimal wholesale prices that sustain information sharing arrangement $K \subset N$ and induce truth-telling are determined by $A_1^k = A_2^k = \frac{a}{2}$, $B_2^k = \frac{1}{2(k+s)}$, $B_1^k = B_2^k + \frac{1}{k+s}D^k$, and a certain positive constant D^k; under such wholesale prices, $K = N$ is the unique dominant strategy equilibrium.

The negative term in w_i^k, for $i \in K$, reduces a participating retailer's wholesale price if he reports a higher signal Y_i. This "good news bonus" offsets the retailer's incentive to distort his signal downward under Cournot competition and hence induces truth-telling.

Although differential wholesale pricing is able to induce full and truthful information sharing, it is unable to coordinate the supply chain. The paper proposes a more flexible pricing scheme with a fixed charge to participating retailers on top of differential wholesale prices. Such differential two-part tariffs are able to coordinate the supply chain when $\beta = 1$ (with perfect substitutes) or achieve near full efficiency (more than 99%) when $0 < \beta < 1$ (with imperfect substitutes), while inducing full and truthful information sharing. The manufacturer is able to extract all supply chain surplus in the former case, but not so in the latter.

2.4 Gal-Or, Geylani and Dukes (2008)

This paper assumes Bertrand competition between two retailers, as studied by some other papers, but it generalizes the information structure as follows: the manufacturer observes a signal x_0 (of the demand shock θ), while retailers observe x_1 and x_2, respectively. The main part of the paper focuses on "one-sided information sharing" where only the manufacturer attempts to disclose her private information and assumes that the manufacturer will do it truthfully.

If a retailer is left outside the information sharing club, he may infer x_0 from the wholesale price. Thus, the model is comparable to the information sharing scenario (S2), with the aggregate retailer information $\sum_{j \in K} Y_j$ replaced by the manufacturer's signal x_0. With two retailers, there are only three arrangements: $K = \emptyset$, i.e., no information sharing (NS); $K = \{i\}$, i.e., partial sharing with retailer i (PSi); and $K = N$, i.e., full information sharing (FS). Within the class of affine wholesale prices $w = \alpha_0 + \alpha x_0$, the following results are shown (Corollary 1 & Proposition 1): The manufacturer's optimal wholesale prices satisfy $w^*_{FS} > w^*_{PSi} > w^*_{NS}$, and her optimal profits satisfy $E(\Pi_{FS}) > E(\Pi_{PSi}) > E(\Pi_{NS})$; In addition, $E(\Pi_{PS1}) > E(\Pi_{PS2})$ if $s_1 > s_2$, i.e., the manufacturer prefers to share x_0 with the retailer who possesses less accurate information.

Notice that the (FS) and (NS) arrangements can also be viewed as special cases of scenarios (S1) and (S3), respectively. Thus, the optimal wholesale prices and manufacturer profits follow the same orders as in Li and Zhang (2008). The driving force is the same signaling (or inference) effect, which alleviates double marginalization under Bertrand competition when direct leakage can be (partially) prevented. In this model, the manufacturer dictates the information sharing arrangement. In practice, she must weigh the incremental benefits and costs from adding an (additional) retailer to the information sharing arrangement. If only one retailer is to be chosen, she should pick the less-informed one. That retailer's need for the manufacturer's information is more acute, so if he had to infer it instead of receiving it directly from the manufacturer, the signaling effect (the pressure to lower the wholesale price) would be stronger.

The paper also studies "two-sided information sharing," which is closer to the model of Li and Zhang (2008). However, the paper only shows the following results for a very special case (Proposition 3): Under two-sided communication with $s_1 = 0$ and $s_2 = \infty$ (i.e., retailer 1 has perfect information and retailer 2 has none), to communicate with only one retailer, the manufacturer will choose the uninformed retailer (retailer 2) if the competition is sufficiently weak (product differentiation high) or the manufacturer's own information is sufficiently accurate; and he will choose the perfectly informed retailer (retailer 1) otherwise.

The intuition lies at the trade-offs between communicating with one of the retailers. On the one hand, the signaling effect favors the uninformed retailer. On the other hand, the value of information to the manufacturer favors the fully informed retailer. In a setting with weak competition or well-informed manufacturer, the former effect dominates the latter. We note that the retailers' incentives, i.e., voluntary participation and truth telling, are not considered in this study.

2.5 Jain and Sohoni (2015)

This paper studies a supply chain with two retailers (R1 and R2) under imperfect Cournot competition. Unlike previous models, the retailers order sequentially under differentiated wholesale prices, as described by the sequence of events below:

(1) M and R1 reach an agreement whether or not to disclose the information $\{w_1, q_1\}$ to R2 later (in stage 4);

(2) M announces wholesale price w_1 to R1;

(3) R1 observes signal Y_1 and orders quantity q_1;

(4) M announces wholesale price w_2 to R2;

(5) R2 observes signal Y_2 and orders quantity q_2;

(6) Ordered units are sold and the market is cleared at the retail price p.

Although Y_1 is not directly disclosed by R1, it can be inferred by M from q_1 in the equilibrium, so after stage 3 the model coincides with the standard model with information sharing arrangement $K = \{1\}$. There are two leakage scenarios with respect to R2: in the full disclosure (FD) case, $\{w_1, q_1\}$ is leaked to R2 in stage 4, which agrees with scenario (S1); and in the no disclosure

(ND) case, $\{w_1, q_1\}$ is not leaked directly although R2 can infer q_1 from w_2 indirectly, which is consistent with scenario (S2) or (S3) (they are identical when $K = \{1\}$).[3]

To sustain nonleakage (ND), it must be beneficial to both M and R1. The paper shows the following: It is harder to persuade M to protect the information than R1; When the competition is intense, M prefers (ND) to (FD) when the relative informativeness of R2 (measured by $x = \frac{1/E[Var(Y_2|\theta)]}{1/E[Var(Y_1|\theta)]+1/\sigma^2}$) is in a medium range; When the competition is weak, M prefers (ND) when x is above some threshold; And a two-part tariff between M and R1 will make it easier to achieve nonleakage.

These results are driven by the interplay of several effects. Nonleakage makes it harder for R2 to learn R1's demand information, but it also diminishes R1's first mover advantage (by using q_1 as a means of deterrence). From R1's perspective, the former effect is positive and the latter is negative. The effects are less clear cut from M's perspective because she has the instrument w_2 to fine tune the implications of the information arrangement.

2.6 Shin and Tunca (2010)

This paper studies a model similar to that of Li (2002) but with two main differences. First, the retailers' demand signals do not come for free. The cost for demand forecasting, $C(v_i)$, is increasing and convex in the precision of the acquired information, $v_i = \sigma^2/E(Var(Y_i|\theta))$. Second, the sequence of events is as follows (where $\mathbf{q}_{-i} = (q_1, \cdots, q_{i-1}, q_{i+1}, \cdots, q_n)$):

(1) M announces price scheme $\{P(q_i, \mathbf{q}_{-i})\}$;

(2) Retailer i makes investment v_i;

(3) Retailer i observes signal Y_i, and orders q_i from M;

(4) Retailer i pays M the total price $P(q_i, \mathbf{q}_{-i})$;

(5) Ordered units are received and sold, and the market is cleared at the retail price p.

Each retailer shares his private information with M indirectly through his order quantity q_i. As all retailers order at the same time, information leakage has no impact on the outcome. More specifically, even though other retailers' order quantities (or the total quantity) may be revealed to retailer i from the payment $P(q_i, \mathbf{q}_{-i})$ charged by M, he has no opportunity to utilize that information. He may regret later the quantity he ordered, which is an issue related to the robustness of the equilibrium.

The paper first considers the case when retailers' information investments cannot be observed by others. It shows that (Propositions 1 and 2): Under the wholesale price contract $P(q_i, \mathbf{q}_{-i}) = wq_i$, or two-part tariff $P(q_i, \mathbf{q}_{-i}) = w_0 + w_1 q_i$, retailers over-invest in demand forecasting compared to the first-best levels, and the loss in supply chain profit can be substantial. The paper

[3] It is shown in the paper that the functions $q_1(w_1, Y_1)$, $w_2(w_1, q_1)$, and $q_2(w_1, q_1, w_2, Y_2)$ (in FD) or $q_2(w_2, Y_2)$ (in ND) are all affine functions.

introduces the so-called *market-based* or *index-based* contracts $P(q_i, \mathbf{q}_{-i}) = w_0 + \overline{p}(\mathbf{q})q_i - w_d q_i^2$, where $\overline{p}(\mathbf{q}) = w_1 + w_2 \sum_{j=1}^{n} q_j$ is the index price and $w_d > 0$ corresponds to quantity discounting. It shows that (Proposition 4) market-based contracts can fully coordinate the supply chain, with respect to both information investments and order quantities.

These results are consistent with the findings in the literature, i.e., the more the manufacturer can commit to nonleakage, the easier it is to induce information sharing and to coordinate the supply chain. To achieve coordination, the price must be adapted to retailers' information, e.g., $\sum_{j=1}^{n} q_j$, which makes the model comparable to the standard model in scenario (S3) with $K = N$. However, the setting is even more stringent in this paper because at the time they place orders, the retailers cannot infer anything about others' signals, and thus direct and indirect leakage is fully blocked in advance.[4]

The paper also considers the case when retailers' investments can be observed by competitors, in stage 2 of the sequence of events. In this situation, each retailer benefits from a higher signal accuracy (known to all retailers) as it makes his competitors more responsive to his order strategy, which creates stronger incentives for over-investment and prevents full coordination even by the market-based contract. As a remedy, the paper shows that a more complex mechanism, the so-called *uniform-price auction*, can achieve full coordination. This mechanism allows the manufacturer to announce a supply function in addition to a price scheme (in stage 1) and the retailers to submit demand functions rather than fixed order quantities (in stage 3). The equilibrium order quantities are determined by balancing the total supply and total demand. In the equilibrium, the order quantity of a retailer is now related to the wholesale price he is facing, which in turn is related to the aggregate demand information. This essentially turns the model into scenario (S3) of the standard model with $K = N$, where the retailers can infer the aggregate demand information from the manufacturer's wholesale price before ordering.

2.7 Shamir (2012)

Shamir (2012) provides a different perspective to the issues raised in prior works by suggesting that retailers may in fact have an incentive to share information with their competitors and the manufacturer. The paper considers a model similar to Li and Zhang (2008) with one manufacturer supplying N (≥ 2) retailers in price (Bertrand) competition. There are two scenarios: the retailers may share information only with other retailers (horizontal information sharing) or may share information with the manufacturer too in addition to their competitors (public information sharing). Note that the scenario with public information sharing is similar to scenario (S1) in Table 2 but it is the retailers here who initiate the sharing of information rather than the manufacturer.

The paper shows the following results: when the information can be verified, every retailer

[4] Indirect leakage occurs only after the orders are made, through the index price $\overline{p}(\mathbf{q})$. However, as shown in the paper (Proposition 5), the retailers' equilibrium strategy is *regret-free*, i.e., they have no incentive to alter their order quantities after learning other retailers' quantities.

is better off by sharing his private information with other retailers (horizontal) and a retailer is better off as more retailers share their private information (Proposition 1); a retailer is worse off by sharing information with the manufacturer, i.e. in the "public sharing" setting (Proposition 2). The first result is a natural consequence of the Bertrand model. The second result follows from the fact that the manufacturer will extract rent and make the retailer worse off under vertical information sharing, similar to the insight in other papers.

Next, a scenario is considered where a retailers' information cannot be verified so he can engage in cheap talk. In this case, it is shown that: retailers have no incentive to share information truthfully and accurately in either the horizontal or public information sharing scenarios (Propositions 3, 4, 5).

Finally, the paper considers a setting where the retailers can design a mechanism to signal their private information truthfully while maximizing their profits. It shows that in some situations the retailers prefer sharing information publicly to horizontally, i.e., it is beneficial to invite the manufacturer into the information sharing club (Proposition 12). It also shows that retailers incur a higher cost for reporting a high signal (good news) in the horizontal information sharing setting and a high cost for reporting low demand (or bad news) in the public sharing case. This is consistent with the insight that retailers have a natural incentive to inflate demand in the horizontal sharing setting (so as to keep retail prices high) and to deflate demand in the public sharing case (so as to keep wholesale prices low).

3 Ex-Post Information Sharing Arrangement

In the previous section, information sharing arrangement between the manufacturer and retailers is pre-determined at the beginning, after which, the parties do not concern with the question of whether or not to share (or leak) information. In addition, when the (aggregate) information is inferred instead of directly leaked, it can be inferred perfectly, i.e., only separating equilibria are considered. A stream of papers, starting with Anand and Goyal (2009), deviates from these assumptions.

3.1 Anand and Goyal (2009)

This paper studies a supply chain with one manufacturer (or supplier) and two retailers, an *incumbent* and an *entrant*, engaging in Cournot competition. The inverse demand function is given by $p = \widetilde{a} - (q_i + q_e)$, where q_i and q_e are the order quantities of the incumbent and the entrant, respectively, and $\widetilde{a}$ can be a_H with probability ρ or $a_L (< a_H)$ with probability $1 - \rho$. Only the incumbent can observe the exact $\widetilde{a}$ because of his familiarity with the market. We refer to the incumbent as the high (or low) type when $\widetilde{a} = a_H$ (or a_L). The sequence of events is as follows:

(1) M announces wholesale price w;

(2) Incumbent observes $\widetilde{a}$ and places an order q_i with M;

(3) M decides whether to leak the information q_i to the entrant;

(4) Entrant places an order q_e with M;

(5) Retailers receive and sell ordered units, and the market is cleared at the retail price p.

In this model, M does not make any formal arrangement with the incumbent on information sharing and the incumbent does not share the observed $\widetilde{a}$ directly. Keeping the incentives of M and the entrant in mind, the incumbent plays the Stackelberg leader in a signaling game. He must determine whether or not to let the supplier infer the correct $\widetilde{a}$ through his order q_i and foresee whether M will leak that information to the entrant. He has two options. First, he can order different quantities given different $\widetilde{a}$, which will reveal the true $\widetilde{a}$ to M and is called a *separating strategy*. Second, the incumbent can order the same amount regardless of $\widetilde{a}$, which will prevent M from inferring the demand information and is called a *pooling strategy*. In both cases, M needs to decide whether or not to leak q_i to the entrant.

Given the wholesale price w, define $a'_H = a_H - w$, $a'_L = a_L - w$, and $\mu' = \mu - w$, where $\mu = \rho a_H + (1-\rho)a_L$. Let $\theta = a'_H/a'_L$ be a proxy for demand uncertainty. The paper shows the following results (Propositions 1, 2, & 3): (i) If $\theta \geq 3$, the incumbent orders $q^*_{iH} = a'_H/2$ or $q^*_{iL} = a'_L/2$, contingent on $\widetilde{a}$; M leaks the incumbent's order quantity to the entrant; and the entrant orders $q^*_{eH} = a'_H/4$ or $q^*_{eL} = a'_L/4$ accordingly; (ii) If $\Theta(\rho) < \theta < 3$, the incumbent orders $q^*_{iH} = a'_H/2$ or $q^*_{iL} = (2a'_H - a'_L - \sqrt{3(a'_H)^2 - 4a'_H a'_L + (a'_L)^2})/2$, depending on $\widetilde{a}$; M leaks; and the entrant orders $q^*_{eH} = a'_H/4$ or $q^*_{eL} = [3a'_L - 2a'_H + \sqrt{(a'_H - a'_L)(3a'_H - a'_L)}]/4$ accordingly; (iii) If $1 < \theta \leq \Theta(\rho)$, the incumbent orders $q^*_i = a'_L - \mu'/2$ regardless of $\widetilde{a}$; M leaks; and the entrant orders $q^*_e = (3\mu' - 2a'_L)/4$. The threshold $\Theta(\rho)$ above is a decreasing function of ρ with $\Theta(0) = 3$ and $\Theta(1) = 1$.

The incumbent plays the separating strategy in the first two cases and pooling in the third. The incumbent would always want the entrant to believe that the demand is low ($\widetilde{a} = a_L$) so that he should order less. Thus, the low-type incumbent would prefer M to leak the information and the high-type incumbent would try to mimic the low type. In case (i), the demand uncertainty (gap between the two states) is so significant that the low type can simply choose his optimal quantity under public information, knowing that the high type cannot afford to imitate. The demand information is truthfully revealed and no quantity distortion is exercised. In case (ii), the demand gap shrinks to a level that the low type needs to distort his order quantity downward to be able to escape from the high type. In case (iii), the gap becomes so small that it would be too costly for the low type to separate out.

Why would M always leak the incumbent's quantity? As the wholesale price is fixed, M prefers larger quantities from the retailers. Suppose that the incumbent plays a separating strategy. Without leakage, the entrant will assume an average demand and place a moderate order. If the demand is actually high (revealed by a large order from the incumbent), M will be better off by leaking that information and attracting a larger order from the entrant. Thus, M will leak whenever she infers a high demand, which is as good as leaking in both demand states, because if M does not leak in the low demand state the entrant can infer the (low) demand correctly. Second, suppose that the incumbent plays a pooling strategy. When the incumbent's order is relatively small, the supplier benefits from leaking that information and encouraging the entrant to order more.

3.2 Kong, Rajagopalan and Zhang (2013)

This paper studies a model similar to that in Anand and Goyal (2009) except that it considers a revenue sharing contract between the manufacturer and retailers instead of a wholesale price contract. In a revenue sharing contract, the supplier sells the product to the two retailers at a possibly lower wholesale price, say w, and instead receives a share α of the retail revenue. The sequence of events is identical to that in Anand and Goyal (2009) and the intercept of the inverse demand function is $\widetilde{a} = a_H$ or a_L, with mean $\mu = \rho a_H + (1-\rho)a_L$. It is assumed that the supplier can communicate to the incumbent whether or not she intends to leak the incumbent's order quantity to the entrant, which is credible if the supplier can make a higher profit with the intended action.

First, consider the scenario where the parameters of the revenue sharing contract (w, α) are fixed (announced in stage 1). Let $\theta = \frac{a_H - w/(1-\alpha)}{a_L - w/(1-\alpha)}$. The following result in the paper establishes necessary and sufficient conditions for a nonleakage equilibrium (Theorem 1): "Assume that $\theta \geq \frac{1-\rho}{3(1-\frac{\sqrt{2}}{2})-\rho} \geq 0$ and $\frac{w}{\mu} \leq \frac{1}{2}(\frac{3a_L}{\mu} - 1)(1-\alpha)$. A nonleakage equilibrium exists if $q_{iH}^{N^*} \geq \bar{q}_i$ and $q_{iL}^{S^*} \leq \underline{q}_i$, and only if $\frac{w}{\mu} \leq (\frac{3a_H}{\mu} + 2)\frac{\alpha(1-\alpha)}{12+5\alpha}$ and $q_{iL}^{S^*} \leq \underline{q}_i$." The quantities $q_{iH}^{N^*}$ and $q_{iL}^{S^*}$ are, respectively, the incumbent's optimal order quantities under the nonleakage and separating leakage equilibria. The threshold limits $\underline{q}_i$ and $\bar{q}_i$ are functions of w, α and μ; if the incumbent's order quantity falls within the interval $[\underline{q}_i, \bar{q}_i]$, the supplier prefers leakage to nonleakage. Under leakage, the downstream retailers together may underorder when the demand is low and overorder when the demand is high, compared with the supplier's first-best quantity. This type of quantity distortion may be mitigated in both demand states simultaneously if the supplier does not pass the demand information to the entrant so that the entrant has to order an intermediate quantity, aimed at the average demand. Thus, the supplier may benefit from nonleakage in both demand states. The conditions in the theorem ensure that the incumbent retailer is also better off under nonleakage. This is in contrast to a wholesale price contract, where the supplier always benefits from leaking the incumbent's order quantity; because a larger order translates into higher profit for the supplier, the supplier would always like to inform the entrant when the demand is high. This is no longer true under a revenue sharing contract, where a larger order is not always better for the supplier.

The paper also shows that there exists a set of (w, α) pairs that support a nonleakage equilibrium, referred to as the nonleakage region. The range of wholesale prices that support nonleakage is relatively wide when α lies in the middle of the interval [0, 1] and it shrinks as α moves toward 0 or 1. The case $\alpha = 0$ is equivalent to the wholesale price contract and the result is the same as in Anand and Goyal (2009) that the supplier always leaks. When α increases, the supplier's profit is more in line with the supply chain profit and she is more willing to control the total quantity in the channel by hiding the demand information from the entrant. However, as α approaches 1, the feasible range of w that induces the retailers participation diminishes, resulting in a narrow nonleakage band. The nonleakage region expands when the ratio a_H/a_L is higher. In this case, there is greater demand variation and the incumbent's information advantage exacerbates the quantity distortion from the supplier's perspective and motivates the supplier to prevent information leakage.

The paper shows that the total supply chain profit may increase under nonleakage. More interestingly, not only do the supplier and incumbent benefit from nonleakage, but sometimes even the entrant can be better off under nonleakage. This is because while nonleakage prevents the entrant from adjusting the order quantity based on better demand information, the entrant benefits from being able to place an order simultaneously with the incumbent under nonleakage rather than sequentially under leakage.

The paper shows that the results are robust even if the wholesale price is endogenous, given a revenue sharing rate. Specifically, there exists a threshold on the revenue sharing rate α above which the supplier's optimal wholesale price lies in the nonleakage region. Moreover, this threshold decreases as the ratio a_H/a_L increases. This suggests that as the demand states become more distinguishable, a smaller share of revenue is needed to persuade the supplier not to leak.

The paper also shows that the revenue sharing contract continues to be attractive in terms of preventing information leakage when some of the model assumptions are relaxed or altered. It is shown that the nonleakage region will be larger when: (i) the incumbent could place a larger order and hold back (i.e., not sell) some units to achieve a higher retail price, (ii) the entrant may choose to ignore information provided by the supplier. Finally, it is shown that there exists a substantial nonleakage region even if the incumbent does not have a first mover advantage and the incumbent and entrant play a simultaneous (rather than sequential) game after the supplier has leaked the information to the entrant. Overall, the incentives of the supplier and retailers are better aligned under revenue sharing and the supplier is not simply trying to push product under all circumstances as in a wholesale price contract.

3.3 Shamir (2015)

Shamir (2015) considers a framework with one manufacturer supplying N retailers who compete on price. Unlike other papers with a Bertrand model, such as Shamir (2012) and Li and Zhang (2008), this paper considers a Bertrand game with perfect substitutes (or *homogeneous products*). It also assumes that the retailers share information *after* observing their private signals. While prior works (both ex-ante and ex-post models) focus on the negative effects of information leakage and how it might motivate retailers to not share information, this paper takes a counter-intuitive perspective, like Shamir (2012). In particular, it considers the possibility that a retailer may want to share information with the manufacturer expecting that it will be disclosed through the wholesale price to other retailers, with the wholesale price acting as a collusion device.

Each retailer i gets a private signal $Y_i \in \{H, \phi\}$ about the market condition, which can be high or low. If actual demand is high (H), the retailer has a probability ρ of learning that it is H (informative signal). If actual demand is low (L), then the retailer only observes the non-informative signal ϕ. Upon observing the signal Y_i, retailer i updates the probability that the market condition is H in a Bayesian fashion. The paper considers an infinite horizon repeated game where demand and private signals in each period are independent and identically distributed and the entire history of wholesale and retail prices is observable by all entities. The paper explores three different information sharing scenarios: retailers share their private demand information horizontally with other retailers and collude (I1); they do not share any demand information (I2); they share their demand information solely with the manufacturer (I3).

In setting (I1), it is shown that retailers (i) can collude and set a monopoly price and (ii) do not have an incentive to share information with the manufacturer (Lemma 1). In scenario (I2), where they cannot share information and collude, two possible settings are considered: retailers follow a rigid price that they all follow each period or retailers can set a price each period based on their observed private signals. They obtain the following result: as the number of retailers increases above a threshold, the retailers will gravitate towards using a rigid pricing scheme rather than variable prices based on their private signals each period (Proposition 3).

This is because the likelihood that at least one retailer receives a non-informative signal increases as the number of retailers increases. A retailer receiving a non-informative signal will set a low price and the retailers who have an informative signal will get zero profits. Thus, the retailers are not able to coordinate and collude using variable pricing and the cartel prefers to use a rigid pricing scheme and ignore the private information of its members.

In setting (I3), where retailers share private demand information with the manufacturer, it is shown that the manufacturer will set one of two wholesale prices w_H or w_ϕ depending, respectively, on whether they receive an informative or non-informative signal (Proposition 4). The retailers infer, on observing w_H, that at least one retailer has received an informative signal and infer that all the retailers have received the non-informative signal when the manufacturer chooses w_ϕ. The manufacturer has to distort the wholesale price down in the non-informative case if demand uncertainty is not high to send a credible signal and achieve a separating equilibrium. This distortion is similar to the distortion in the wholesale price in Gal-Or et al. (2008). It is shown that (Propositions 5 and 6): when (i) the number of retailers is large enough so that a rigid pricing scheme is preferred in (I2) and (ii) demand uncertainty is high enough, setting (I3) is preferred to (I2) by both the manufacturer and retailers.

As a result, information is shared vertically with the manufacturer who uses it to determine the wholesale price. Overall, vertical information sharing through the manufacturer is preferred as a means to collude when the number of retailers is high or demand uncertainty is high. Further, it is shown that consumer surplus may actually be lower when the retailers collude by sharing information through the manufacturer instead of directly with each other. The manufacturer benefits from the information sharing and this in turn increases the manufacturer's profit at the expense of consumer surplus.

4 Other Dimensions

4.1 Uncertain Costs

Li (2002) also analyzes the case where the uncertainty (and private information) is about the retailers' marginal costs C_i. The retailers engage in perfect Cournot competition. Stage 2 in the basic sequence of events is modified to:

(2) Each retailer i observes cost C_i and, if $i \in K$, shares it with M.

The following assumptions are made: (1) C_i's are identically distributed with (normalized) mean 0 and variance σ^2; (2) $E(C_i|C_{-i}) = \alpha_i^i + \sum_{j \neq i} \alpha_j^i C_j$, where $C_{-i} = (C_1, \cdots, C_{i-1}, C_{i+1}, \cdots, C_n)$ and $\alpha_j^i \geq 0$ for all i and j. Thus, C_i's are positively correlated. The above assumptions are satisfied by the multivariate normal distribution. Similar to the uncertain demand case, these assumptions lead to the convenient property that $E(C_i|C_j, j \in K) = \frac{1}{k+s} \sum_{j \in K} C_j$, $i \in N \backslash K$, where $s = (1-\rho)/\rho$ and $\rho = Cov(C_i, C_j)/\sigma^2$.

The paper shows: given any $K \subset N$ and realized $(C_j)_{j \in K}$, in a symmetric equilibrium, the sales quantities are given by

$$q_i^*(C_i, w^*) = \frac{1}{n+1} \left(a - w^* + A_1^k \sum_{j \in K} C_j - A_2^k C_i \right), \quad i \in K, \tag{8}$$

$$q_i^*(C_i, w^*) = \frac{1}{n+1} \left(a - w^* + B_1^k \sum_{j \in K} C_j - B_2^k C_i \right), \quad i \in N \backslash K, \tag{9}$$

for some positive constants A_1^k, A_2^k, B_1^k, and B_2^k. It is then shown that (Proposition 9): Given any information sharing arrangement K, the manufacturer is better off by acquiring information from more retailers, and each retailer is better off by disclosing information to the manufacture if $\rho < \frac{2(n^2-n-1)}{2n^2-n-1}$; Thus, when this condition is met, complete information sharing is the unique equilibrium; Otherwise, the equilibrium can be either complete information sharing or no information sharing.

This result is markedly different from the uncertain demand case. The driving force is the indirect (leakage) effect—retailers now benefit from leaking their cost information to competitors! As evident from Eq. (9), it benefits a retailer $j \in K$ to spread the word when his cost is low, i.e., $C_j < 0$, which more than compensates for the loss from sharing the information when his cost is high. This positive leakage effect dominates the negative direct effect (of loss of profit to the manufacturer). When the correlation among the costs is relatively small or the number of retailers is relatively large (so that $\rho < \frac{2(n^2-n-1)}{2n^2-n-1}$), it is the unique equilibrium. When ρ is above the threshold, complete information sharing is not the only equilibrium. However, in the uncertain cost case, the manufacturer can always purchase information from the retailers and make every party better off (than not sharing information).

4.2 Auction

Chen and Vulcano (2009) consider a supply chain with one supplier and two resellers in a two-stage game. The two resellers engage in Cournot competition, with the maximum possible demand $\theta = \theta_0 + s_1 + s_2$, where s_1 and s_2 are independent and uniformly distributed random variables and are privately and individually observed by the resellers at the beginning. In the first stage, the supplier auctions her capacity as a bundle to the resellers. Each reseller bids for the capacity based on their own demand signal. The supplier announces the winner and the bid. The winner's bid is disclosed under a first-price auction, whereas the loser's bid is disclosed under a second-price auction. In either case, one of the resellers' information is revealed through the auction and the other's is hidden. In other words, the winner has information advantage under a second-price auction and the loser is more informed under a first-price auction. In the second stage, the two resellers compete in the consumer market. The winner has first-mover advantage in the second stage. The competition game can be decried as follows:

Under a second-price auction, the winner has full information of the two signals (s_w from the winner and s_l from the loser) and his objective can be represented by: $\max_{q_w}(\theta - q_w - q_l)q_w - c(q_w - C)^+$, where q_w and q_l are the winner and loser's order quantities, respectively, C is the auctioned capacity, and c is the unit cost in the spot market. The loser's decision is only based on his own signal s_l and his objective is: $\max_{q_l} E_{s_w}[(\theta - q_w - q_l - c)q_l | s_w > s_l, s_l]$. In contrast, under a first-price auction, the winner and loser's objectives are: $\max_{q_w} E_{s_l}[(\theta - q_w - q_l)q_w - c(q_w - C)^+ | s_w > s_l, s_w]$ and $\max_{q_l}(\theta - q_w - q_l - c)q_l$, respectively.

The paper finds that the possibility of revealing the bidders' private information leads to lower bids in equilibrium than under the conventional auction without resale, regardless of the auction form. However, the form of auction affects the total quantity in the consumer market, contingent on the difference in the resellers' signals: if the signals are far apart, the first-price auction helps the loser to get access to the high demand signal from the winner and hence increase his order quantity; while if the signals are close, the second-price auction helps to maintain a high order quantity. In addition, as the first-price auction reveals the winner's private information and thus decreases his willingness to pay, the supplier gains a higher payoff under the second-price auction. The second-price auction also improves both resellers' payoffs by aligning the winner's first-mover and information advantages and reducing the downstream competition.

4.3 Competing Supply Chains

Ha, Tong and Zhang (2011) consider two competing supply chains each with one manufacturer and one retailer. The retailers have private information about demand and may choose to share or not share demand with their respective manufacturers. The manufacturer has production diseconomies, i.e. increasing marginal cost. The sequence of events is as follows in each of the two supply chains: the manufacturer may pay the retailer for sharing information and the retailer can decide whether to share information; next, demand is revealed to the retailer which they will share (truthfully) or not share depending on the decisions at the first stage; the manufacturer then sets the wholesale price followed by the retailer either deciding quantity (Cournot) or price (Bertrand)—both models of retail competition are considered. The cost of information sharing and wholesale price in one supply chain are not available to the competing one. The paper shows that information sharing in one supply chain triggers a competitive reaction from the other chain which is damaging to the first chain in the Cournot model but may be beneficial in a Bertrand model. Information sharing benefits a supply chain if production diseconomy is large and competition is less intense in both models. Moreover, a supply chain may be worse off by improving information accuracy or reducing production diseconomy if it results in the rival chain not sharing information within it. In the Bertrand model, the manufacturer may be worse off by receiving information which does not occur in the Cournot model.

Shamir and Shin (2015) consider a structure similar to Ha et al. (2011) with two competing supply chains comprising of one manufacturer and one retailer each. One chain is an incumbent with the retailer in that chain having a private signal of demand information not available to the other chain. Unlike in Ha et al. (2011), it is not assumed that the retailer will share it truthfully with the manufacturer. The manufacturer makes capacity decisions based on the retailer's information and the wholesale prices are exogenous. The retailers compete in quantities (Cournot). The sequence of events is as follows: the incumbent retailer observes a signal; he may (or may not) share information with only his manufacturer (scenario I1) or publicly (I2); the entrant firms may or may not enter the market; the incumbent or both manufacturers set capacity levels; the incumbent or both retailers observe market demand and then order quantities. When information is shared only within the incumbent supply chain (I1), the incumbent retailer has an incentive to manipulate the shared information in order to secure sufficient capacity. However, when the information is shared with the competitor as well (I2), the incumbent retailer considers the trade-off between the benefits of obtaining sufficient capacity in the high demand scenario and the cost of more intense competition with the entrant. A key result in the paper is that by making information available to the competitor, it is possible to achieve separation between a retailer observing a high demand and a low demand. The retailer benefits sufficiently in the high demand scenario from the increased capacity although this comes with increased competition. In the low demand case, the retailer benefits by truthfully revealing his demand signal as it weakens retail competition. The paper also shows that the incumbent retailer may prefer to share information publicly relative to committing to a minimum purchase quantity as part of an advance purchase contract.

5 Discussion and Future Research

5.1 Discussion of the Existing Literature

A number of interesting and common insights can be gleaned from the literature about information sharing and leakage. As discussed in the introduction, leakage of information (or at least the fear that there will be leakage) often occurs in a supply chain when a retailer shares information vertically with a manufacturer. The literature, focusing primarily on demand information, has shown that vertical sharing of information by retailers with manufacturers always results in a negative effect on the retailers as the manufacturer extracts some of the surplus – this is true in both Cournot and Bertrand models of competition at the retailer level. However, the effects of the manufacturer leaking this information to retailers (horizontal sharing) can have a positive or negative effect, respectively, depending on whether the competition among retailers is on price or quantity and whether their products are substitutes or complements. The literature has shown that the negative effects of vertical sharing are dominant enough that no information sharing is the equilibrium outcome in the majority of scenarios. This is shown to be true independent of whether information sharing arrangements are made before or after private information is revealed. The level of accuracy of private information among different entities also plays an important role. In general, when retailers have similar levels of accuracy or the accuracy is low, information sharing is more likely and leakage less likely. When information accuracy among retailers is asymmetric, the manufacturer is more likely to leak to the less informed retailer. Finally, the results also depend on whether two competing retailers move simultaneously or sequentially and the level of demand uncertainty.

To incentivize truthful information sharing despite the potential for leakage and its negative effects, the literature has come up with a variety of solutions: side payments by manufacturers to retailers (Li 2002), different wholesale prices charged to different retailers (Jain et al. 2011), revenue sharing contracts (Kong et al. 2013), market-based contracts (Shin and Tunca 2010) and costly actions (signals) by retailers (Shamir 2012). In addition, retailers can enter into a binding confidentiality agreement to prevent leakage which in turn facilitates information sharing. Some of these solutions can coordinate the supply chain and sometimes benefit all the entities, including ones that do not have private information. A few recent papers also suggest that retailers may have less to fear and may even benefit from leakage of information to their competitors and such sharing may even serve as a collusion mechanism (Shamir 2012, 2015). However, these results are true only when the retailers compete on prices and only under certain conditions.

While anecdotal evidence from industry as discussed in the introduction suggests that firms primarily fear direct leakage of information, the academic literature has shown that indirect

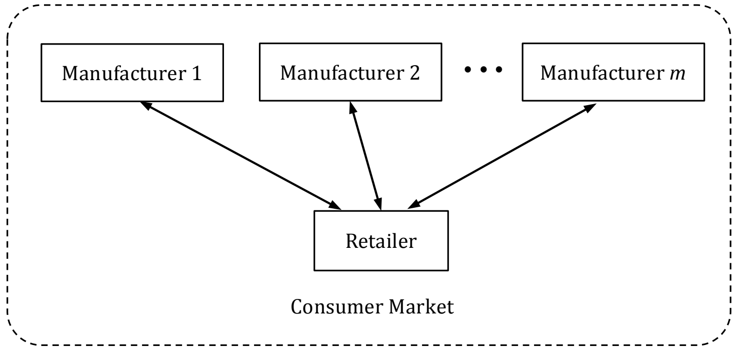

Figure 2: Another common supply chain structure, with one retailer and multiple manufacturers.

leakage of information can have as significant an effect on the incentives to share information as direct leakage. Furthermore, while real-world firms primarily worry about the negative effects of information being leaked to their competitors (horizontal sharing), academic research suggests that vertical information sharing always has negative effects while horizontal sharing and leakage may have a positive or negative effect. However, this is primarily because the academic literature reviewed here has focused on the negative effects of vertical information sharing and not considered the benefits. In the real world, some of the solutions offered in the literature such as side payments by manufacturers, revenue sharing contracts and confidentiality agreements are adopted to address the issue of information leakage as well as other potential negative effects of information sharing.

5.2 Other Supply Chain Structures

The current literature on information sharing and leakage has focused on the supply chain structure with a single manufacturer (supplier) and multiple retailers who have private information on the market demand, as illustrated in Figure 1. In reality, a retailer often buys a type of product from multiple manufacturers (suppliers) and the manufacturers, as well as the retailer, have private knowledge about certain aspects of the consumer market. Thus, the supply chain structure illustrated in Figure 2 is also commonplace, and a natural extension to the current literature is to study this alternative supply chain structure in which the retailer is located at a pivotal junction of the information network.

The first paper to study information flow in such a supply chain is Shang et al. (2015). They consider two manufacturers engaging in a Bertrand competition who supply to one retailer with private information about market demand. The retailer decides whether to share the information with each manufacturer. Their model mirrors the "one-sided information sharing" model of Gal-Or et al. (2008) (consisting of one informed manufacturer and two uninformed retailers) but with notable differences in the game being played, which leads to different insights. Both models capture information disclosure by the informed party to the uninformed ones, and, strictly speaking, are about information sharing rather than leakage. The "two-sided information sharing" model of Gal-Or et al. (2008) seems to be a mirror image of the new model we are proposing. However, they only assume two retailers, one of which has perfect information and the other has no information. More general settings are worth investigation.

We note that the models with mirrored supply chain structures are not really the mirror images of each other. As the wholesale prices are often set (by manufacturers) before the retail prices are set (by retailers), the change of ownership of private information results in a change of the sequence of events in terms of informed and uninformed parties, which may lead to different conclusions as evident from Shang et al. (2015) and Gal-Or et al. (2008).

The new supply chain structure introduces new research challenges and opportunities regarding the type of private information. In the existing literature, market demand is the predominant information under consideration, except Li (2002) who also considers private marginal costs of the informed parties (retailers). In the alternative supply chain, the manufacturers' private production costs pose more interesting questions. Similarly, production capacities that affect manufacturers' competitiveness and profitability are important, yet often private, information. Qian et al. (2012) introduce this dimension to the original supply chain structure and show that if the manufacturer has a capacity constraint, full information sharing can be induced by a discriminative supply rule, i.e., allocating a significantly larger quantity to retailers participating in information sharing when the total demand exceeds capacity. In the alternative supply chain, the capacities of competing manufacturers are valuable information to share or leak.

A more general supply chain structure consists of multiple retailers and multiple manufacturers, as illustrated in Figure 3. This is representative of the real world where, for instance, manufacturers such as Procter and Gamble (P&G) and Colgate Palmolive compete with each other but also supply to retailers such as Target and Wal-Mart who in turn compete for consumers. It will be interesting to study the possibility of information sharing among some members of the supply chain given the possibility of leakage in such a setting, as it raises a host of new questions. For example, as part of initiatives such as CPFR, Target may collaborate with P&G to forecast demand and plan replenishment quantities. Suppose Colgate is planning a promotion in the near future which may impact P&G's sales at Target negatively. This puts Target in a bind as it has to collaborate with P&G to plan demand and order quantities but cannot share Colgate's promotional plans. Conversely, the same type of issue can also arise if Target is planning to promote P&G's products which may impact demand for P&G's products at Wal-Mart but P&G may be unable to share this valuable information with Wal-Mart. In this case, information sharing is impossible without leakage and confidentiality agreements will not resolve the problem. There are many interesting issues of this nature that require further study in such multiple manufacturer, multiple retailer networks.

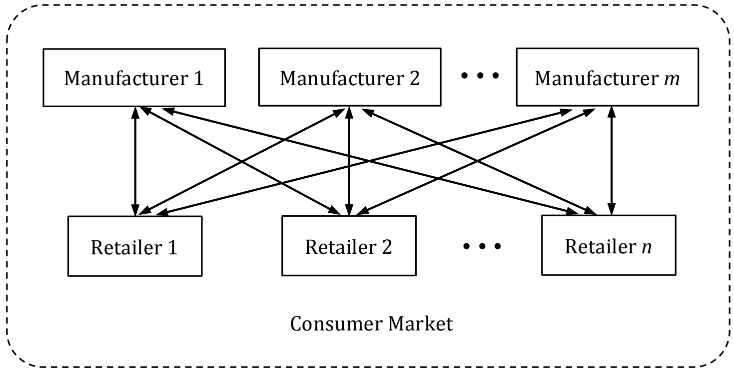

Figure 3: A more general supply chain structure, with multiple manufacturers and retailers.

5.3 Other Types of Contracts

The existing information sharing and leakage literature has focused on the wholesale price contract between manufacturers and retailers, partly due to its prevalence in the real world and partly because of its analytical tractability. However, as evident from Kong et al. (2013), the use of different types of contracts such as the revenue sharing contract may change the results completely, e.g., from leaking information to not leaking. Revenue sharing contracts are popular in some industries such as entertainment, sports leagues, and software (see e.g., Dana and Spier 2001). Other types of contracts, such as buy back and quantity discount, are also adopted in the real world (Cachon 2003). As shown by Li and Zhang (2008) and others, if the intended receiver of some private information can commit not to leak that information to a nonparticipating party, the owner of that information will be more willing to share it. The findings of Kong et al. (2013) reinforce this insight. The revenue sharing contract can align the incentives of supply chain partners better than the wholesale price contract, so the former is more likely to motivate collaboration between the receiver and sender of the information to keep it confidential, which will facilitate information sharing in the first place. We conjecture that other types of contracts or arrangements that help align the incentives of supply chain partners can achieve similar outcomes, which is worthy of future research.

5.4 Long-term Relationship

All papers discussed in this chapter except Shamir (2015) assume one opportunity for each retailer to order from the manufacturer and sell in the consumer market. That is, there is only a single period, albeit multiple stages of interactions. Under such a model, unless a binding confidentiality agreement is in effect, the manufacturer faces no explicit consequence for leaking the retailers' private information. In reality, supply chain members tend to maintain a long-term relationship, and leaking partners' information without their consent will damage their relationship and threaten future business opportunities. Faced with possible retaliation from the retailers in the future, from refusing information sharing to ceasing the business partnership, the manufacturer will be more conservative about leaking retailers' information. Thus, concerns about long-term relationships and reputation may provide sufficiently strong incentives for the manufacturer to protect the retailers' information voluntarily, which can substitute for a legal confidentiality agreement. On the other hand, under some circumstances, the manufacturer may find it even more tempting to leak some retailers' information to others, especially when such information has significant value to other retailers in the future. Long-term relationships and repeated interactions add reality to the model, but introduce new challenges to the analysis as well. They represent another interesting future research direction.

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