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Value Differentiation

Rachael E. Goodhue and Gordon C. Rausser

American agriculture is shifting from homogeneous commodities to differentiated products. Value differentiation, the process by which agrifood chain actors isolate, match, and exploit heterogeneity in consumer preferences and product attributes, is examined. Value differentiation is characterized by complementarities across four activities at each stage of the production chain: product characteristic measurement, product characteristic production, coordination between stages, and customer preference detection. Complementarities at the firm level are modeled using supermodularity. The model's predictions are discussed, as are potential testing approaches, and implications are presented for agrifood firms, marketing orders, and returns to research.

Key words: complementarities, supermodularity, value differentiation

Introduction

American agriculture shows many signs of shifting its orientation from homogeneous commodities to heterogeneous products. The mass consumer markets developed over the course of the prior century are fragmenting into specialized product niches (Manchester 1992, 1994; Kinsey 1994). Consequently, food processors and retailers must precisely identify their targeted consumer groups in order to successfully compete in this market environment. Rapid improvements in information technology have greatly increased their ability to do so. Information technology has also improved quality control and reduced the cost of production at all levels of the agrifood chain. As a consequence, it may have encouraged the increased vertical coordination that has tightened relations among levels of the production and marketing chain. These changes have facilitated serving consumer niche markets with suitably customized products. Biotechnology is anticipated to further lower production costs and increase the ability to control product attributes. This set of changes is referred to as value differentiation. *Value differentiation* is the process by which agrifood chain actors isolate, match, and exploit heterogeneity in consumer preferences and in product attributes.

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Agricultural economists have described exhaustively the changes in agricultural production and marketing listed above (Barry; Boelhje 1995, 1996, 1999; Kinsey 2001; Manchester 1992, 1994; Urban; Zilberman, Sunding, and Khanna). Some observers credit technological change, particularly information technology and biotechnology, with driving the transformation process, but do not evaluate the nature of the resulting changes (Streeter; Urban). A closely related body of work uses the transaction costs framework, initiated by Coase and developed by Williamson and others, to provide an explanation for the features of the transformation process (Barkema 1993, 1994; Drabenstott). While this literature has explained the exogenous forces underlying the transformation of agriculture, it does not attempt to explain the nature of firms' responses to these forces.

Formal analyses of changes in agriculture tend to focus on a single specific change—such as the movement from spot markets to contracting, the effects of market power, or the increased importance of proprietary intellectual property—rather than examining the overall transformation process. Existing hypotheses regarding a single change, such as the explanations of increased vertical integration (e.g., Perloff and Rausser; and Hennessy), cannot explain the nature, speed, or extent of the transformation process as a whole.

The agricultural economics literature's emphasis on description of value differentiation, and its associated restriction of formal analysis to individual changes, is due in large part to the inadequacy of conventional marginal economic analysis. The very analytical requirements (e.g., continuity, differentiability) which have made marginal analysis such a powerful tool in so many contexts limit its applicability to multicausal, integrated processes. The failure of standard economic tools to explain interactions of different changes in an integrated framework has long been reflected in the orientation of the agribusiness literature (see, for example, Goldberg).

Oriented toward agrifood decision makers, the agribusiness literature has focused on analyzing product systems and their evolution rather than on largely independent questions of market power and innovation. This analysis proposes to bridge the gap between the problem-oriented agribusiness literature and the agricultural economics literature. An analytical firm-level model of value differentiation is introduced that is not dependent on marginal analysis, or on differentiability more generally. Moreover, the model provides a firm-level testable explanation of the interactions observed but not explained by agribusiness researchers.

The observed and predicted changes associated with value differentiation are grouped into four processes at each production stage: (*a*) the determination of customer preferences, (*b*) the detection of product attributes, (*c*) the production of these attributes, and (*d*) coordination with other stages of the production chain. A firm-level model of the transformation process is then developed based on the existence of complementarities across these four activities. In such a framework, changes that promote any one of these activities may promote all of them. The interactions at the heart of value differentiation are captured by supermodularity. Supermodularity has been used by Milgrom and Roberts, and by Milgrom, Qian, and Roberts to examine developments in manufacturing, such as just-in-time inventory systems, and how they are related.

Hennessy, Roosen, and Miranowski utilize supermodularity across firms to examine the potential role of leadership in providing increased food safety. Safer food can be interpreted as a case of increased product differentiation. Their focus is on leadership in a multi-firm context. They evaluate when sufficient surplus is generated in order to induce one member of the supply chain to take an initial action which improves food safety. When actions across firms are complementary, a leader may be able to prompt other firms to increase their food safety efforts. Due to their treatment of multiple firms, Hennessy, Roosen, and Miranowski address the issue of bargaining over the surplus generated by increased food safety. In the current analysis, rather than focus on the supermodularity of decisions across firms, and the associated division of surplus, we focus on the interrelatedness of product differentiation (including potentially greater food safety) with other technology choices for a single firm that may be engaged in multiple stages of production.

Although our use of a firm-level model prohibits the modeling of strategic interactions among firms (as in Hennessy, Roosen, and Miranowski), it provides insight into other factors driving firm behavior. Our framework can explain the observations of the existing literature and provides conditional qualitative predictions regarding the evolution of the agrifood industry. It is consistent with the value chain, or supply chain, perspective, which focuses on the competition between supply chains for consumers' spending, rather than on the division of rents among members of a given chain (Boehlje 1999).

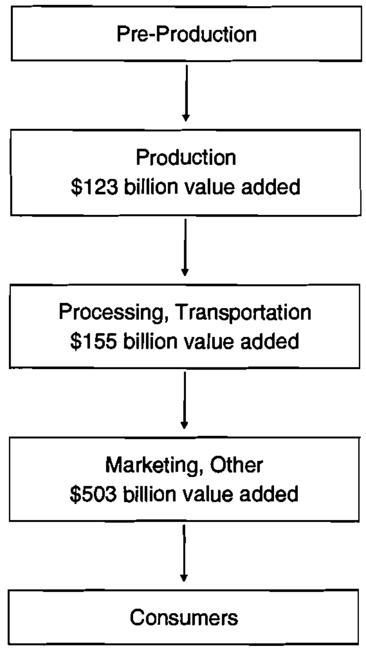
Conceptually, the present work is linked to the increasing returns work of W. Brian Arthur (1994, 1996). Arthur posits a framework where a system can undergo periods of extremely rapid change. Under the increasing returns specification, there are economies of scale across firms. This framework can explain the tendency of some industries to evolve toward a single standard, even when the successful standard is likely inferior from the standpoint of economic efficiency—as may have been the case with the QWERTY keyboard (David).

Another formulation for such interactions in the economic literature is network externalities. Among consumers, the adoption of a new standard may be interpreted as a coordination problem. On the supply side, firms have an incentive to increase their number of users through tactics such as penetration pricing (Katz and Shapiro 1986). Alternatively, firms may choose to cooperate, and use a single product standard, so that their products are compatible (Katz and Shapiro 1985).

These analyses examining increasing returns to scale and network externalities bear some resemblance to Rostow's early work on the stages of development and takeoff points for an economy. While Rostow's linear progression of development has been abandoned by later development theorists, his conceptualization of a takeoff point bears a striking resemblance to the dynamic consequences of our framework. In particular, Rostow proposed that once an economy accumulates sufficient savings for investment, the necessary infrastructure, and a government capable of managing a more regionally integrated society, it will begin to grow and to reallocate resources from agriculture to industry and services. In our framework, once a firm has increased its levels of complementary activities to a point where the marginal gains to further increases are mutually reinforcing, the levels of all of the complementary activities will increase in response to a shock that directly promotes any one of these activities.

Modeling Value Differentiation

We focus on product differentiation, the identification of product characteristics for which consumers are willing to pay (and which can be profitably produced, given this willingness to pay), rather than on some absolute measure of product "quality." The food



Notes: All values were obtained from Gallo (1998). The 1996 value of agricultural production includes domestic farm production only; $27 billion in imported agricultural products and $11 billion in seafood were also utilized in the food marketing system.

Figure 1. Stylized stages of the food production chain and 1996 value added

production chain can be described according to the roles played by a few basic actors. Specifically, input suppliers provide genetic material, fertilizer, etc.; producers engage in activities such as raising and harvesting crops, milking cows, or fattening animals to slaughter weight; assemblers organize the product for use by processors; and processors take this output and modify it to create food products, such as flour, bread, cheese, and meat. These food products are then sold to wholesalers and retailers (see figure 1). For discussion purposes, assemblers and processors will be jointly referred to as processors, and wholesalers, retailers, food services, and restaurants as marketers.

These stages are represented by a vertical production chain with σ stages. A firm chooses to engage in $S \leq \sigma$ of these stages. The firm's S stages are indexed by s. The quantity q is assumed to remain unchanged as it moves through the production chain, so that one unit of output for stage s uses one unit of input from stage $s-1$. A firm engages in one or more stages of production. In each stage, the firm engages in four activities: (a) product differentiation, or modifying product attributes; (b) attribute detection, or determining the attributes of inputs from stage $s-1$; (c) preference determination, or identifying the attributes desired by customers in stage $s+1$; and (d) coordination with stages $s-1$ and $s+1$. These processes are illustrated for a single stage of the production chain in figure 2. The firm's profit-maximizing choices of the four activities are affected by two exogenous variables: consumer preferences, and technology.

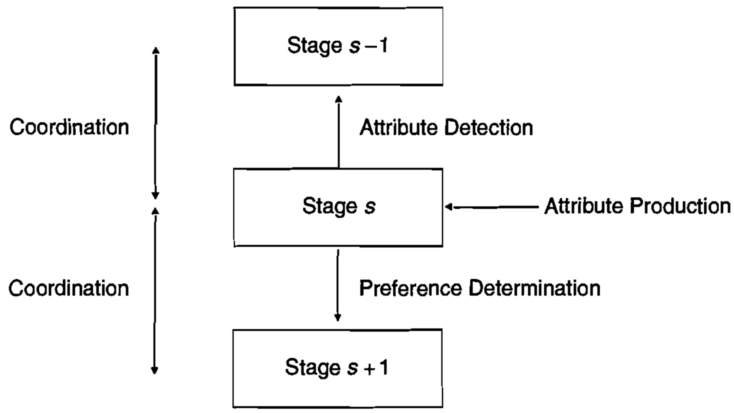


Figure 2. The value differentiation process at stage *s*

Stages of Production Activities

Product Differentiation

In each stage, a firm can increase product differentiation at some nonnegative cost. This cost is affected by the firm's research and technology choices, as well as by exogenous innovations, and is part of the firm's total cost of producing a given quantity q differentiated by the attribute bundle z_s. As z_s increases, product attributes become more specifically differentiated. Within this framework, differentiation may be real or perceived; nothing in the model eliminates the possibility that differentiation occurs through advertising and other image-building efforts, provided these activities are costly.

The firm will not undertake increased differentiation unless it is profitable to do so. The price it receives for its output, $p_{s,s+1}$, is a function of its degree of product differentiation, z_s. No assumption is made about the firm exercising market power when choosing this price. Regardless of its competitive behavior, the firm will choose the profit-maximizing degree of differentiation in this framework.

Attribute Detection

When the product passes from stage $s-1$ to stage s, stage s must discover whether or not the product possesses the attributes required for its production process, which is costly. The cost of discovering product attributes may involve costs of grading, obtaining adequate supplies with necessary attributes, testing for specified attributes, and similar activities. Attribute detection is denoted by μ. As μ increases, the firm increases its attribute detection activities.

Preference Determination

There is a similar process, which goes in the opposite direction: each stage of the production chain must determine what sorts of attributes are desired by the downstream level. Preference determination is denoted by δ. Preference determination is costly. At the intermediate production levels, it is costly for firms to determine the product attributes desired by the buyers of their output. At the final demand level, it is costly for the firm to increase its knowledge of consumers' attribute preferences, indexed in terms of z. An increase in δ corresponds to an increase in preference determination activities.

For example, a grocery store may choose to collect information about its customers by introducing "club cards" which allow the store to collect information about the purchases of individual customers. To do so, the store must invest in the cards and necessary tracking equipment, the labor and expertise to analyze the results, and must induce customers to sign up for the cards through discounts and other promotions tied to the card. Exogenous consumer preferences are designated by τ. Increases in τ are characterized as an increased willingness to pay for differentiated product attributes.

Coordination

The attribute detection and preference determination processes are commonly believed to be influenced by the degree of coordination among stages of the production chain. Coordination ranges from spot markets through contracts and other intermediate measures to complete vertical integration.[1] Coordination is costly. A greater degree of coordination may reduce the costs of determining whether an input possesses specific attributes, or of determining the input needs of the downstream stage.[2] The degree of coordination between stages s and $s - 1$ is indexed by $I_{s,s-1}$, and the degree of coordination between stages $s + 1$ and s by $I_{s+1,s}$.

For example, a survey of large hog packers found that one significant advantage of long-run contracting was an increase in hog quality and a more consistent supply of hogs, relative to using only the spot market. This finding was consistent with the information on contract terms the packers reported; approximately half either required the use of specific genetics or specified minimum quality standards in the contract (Lawrence et al.).

Technology and Profits

Technology

The firm must select technology that determines the costs of production, attribute detection, preference determination, and coordination. These technology decisions are affected by generally-available technology, such as information technology and transportation infrastructure. Generally-available technology is designated by ξ. Technology is costly. Increases in generally-available technology reduce the cost of a specified technology bundle to the firm. For example, in the processing tomato industry, the widespread availability of cellular phones at low prices has decreased the cost of coordinating in-field harvesting with the immediate needs of the processing plant.

The firm may also choose to engage in proprietary research. Expenditures on proprietary research (ρ) generate new technologies. In contrast to generally-available

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[1] We abstract from the strategic considerations involved in using contracts and other intermediate measures of coordination.

[2] Hennessy models the interaction between the degree of vertical coordination and the cost of discovering product quality.

technologies, the availability of these technologies is endogenously determined by research expenditures. For example, strawberries are extremely perishable. Their post-harvest shelf life is limited. Currently, the primary means of ensuring that berries reach their destination and are sold in marketable condition is by regulating when they are picked. California shipments intended for the East Coast are picked at a far earlier stage of ripeness than those intended for local delivery. A proprietary strawberry variety with a longer shelf life could reduce the cost of providing ripe, yet not overripe strawberries, because picking and shipping management decisions would not be as vital at the margin.

If a firm does not operate in some stage s, then it costs nothing to choose a technology with zero production costs and no output. The firm's selection of its stages of production and their degree of integration based on costs of attribute detection, preference determination, and coordination is a continuous version of the Coasian discrete firm decision between markets and integration (Coase).

Profits

The activities discussed above influence the three components of profits (Π): revenues, variable costs, and fixed costs. The firm's revenues are a function of the price for which it sells its output ($p_{s+1,s}$), its product differentiation choice (z_s), exogenous consumer preferences (τ), and exogenous generally-available technology (ξ). A stage s product which provides more of the ultimate z_s desired by consumers will be more valuable to its purchaser.

Variable costs depend on the quantity produced, the differentiated attributes of the product received from stage $s-1$, and exogenous parameters for consumer preferences and generally-available technology. Variable costs are denoted by $c_s(q(p_{s+1,s}, z_s, \mathbf{t})$, where $\mathbf{t}$ is the vector of exogenous variables (ξ, τ).

Fixed costs depend on the differentiated attributes of the product received from stage $s-1$, the levels of the complementary activities, and exogenous parameters for consumer preferences and generally-available technology. Fixed costs are denoted by $k_s(\mathbf{x}_s, z_s, \mathbf{t})$, where $\mathbf{x}_s$ is the vector of non-quality decision variables for stage s ($\rho, \mu, I_{s,s-1}, I_{s+1,s}, \delta$).

For a firm in the production chain, its profits are the sum of its profits at all S stages of production in which it chooses to participate in order to maximize profits. Costs and revenues are zero for stages $s \notin S$. The firm's profit function may be written as follows, where subscripts indicate values for a particular stage s, and the lack of a subscript indicates a vector or matrix which includes all σ stages:

$$(1) \qquad \Pi(\mathbf{p}, \mathbf{x}, \mathbf{z}, \mathbf{t}) = \sum_{s\in\sigma} p_{s+1,s}\, q(p_{s+1,s}, z_s, \mathbf{t}) - c_s\big(q(p_{s+1,s}\, z_s, \mathbf{t}), z_s, \mathbf{t}\big) - k_s(\mathbf{x}_s, z_s, \mathbf{t}).$$

Below, two cases involving $p_{s+1,s}$ are evaluated: one where it is a choice variable, and one in which it is exogenous.

When the components of the above profit function have certain properties, the four activities identified as elements of value differentiation will be mutually reinforcing, or complementary. For example, increasing the production of desired product attributes at stage s increases the value of detecting preexisting attributes as well as the other component activities. The agribusiness literature has identified a number of changes that are simultaneous, or nearly so; the mutual complementarity of these component activities would explain such observations. A change in the value of an exogenous parameter would shift the optimal values of each activity. Complementarity across activities would result in a shift from one cluster of activity levels to another.

Supermodularity and Complementarity

The notion of complementarities is formalized using the mathematical concept of supermodularity. Supermodularity captures the idea that jointly undertaking certain activities will create benefits which could not be realized by undertaking each activity separately; i.e., there are benefits created by adopting the complementary activities as a group. Equivalently, the marginal revenue product of any one activity understates the benefit of its adoption if the other complementary activities are adopted simultaneously. The additional benefits captured by simultaneously performing the activities are popularly termed synergies.

Formally, a function $f: \Re^n \Rightarrow \Re$ is *supermodular* if, for all $\mathbf{x}$, $\mathbf{x}' \in \Re^n$,

$$f(\mathbf{x}) + f(\mathbf{x}') \leq f(\mathbf{x} \vee \mathbf{x}') + f(\mathbf{x} \wedge \mathbf{x}'), \tag{2}$$

where $\mathbf{x} \wedge \mathbf{x}'$ is the vector of minimum elements whose ith element is defined as $x_i \wedge x_i'$, or the minimum of x_i and x_i', and $\mathbf{x} \vee \mathbf{x}'$ is the vector whose ith element is defined as $x_i \vee x_i'$, or the maximum of x_i and x_i'. The Cobb-Douglas production function, for example, is supermodular in its arguments, provided all exponents are nonnegative, such as where $f(\mathbf{x}) = x_1^{1/2} x_2^{1/2}$, $\mathbf{x} = (4,9)$, and $\mathbf{x}' = (1,16)$. Then $f(\mathbf{x}) + f(\mathbf{x}') = 6 + 4 < 3 + 8 = f(\mathbf{x} \vee \mathbf{x}') + f(\mathbf{x} \wedge \mathbf{x}')$.

The supermodularity of a function is not related to its returns to scale; supermodularity is defined exclusively in terms of ordinal rank, whereas returns to scale are cardinal. Supermodularity is not dependent on whether a function is concave or convex; any function of a single variable is trivially supermodular. While conceptually the idea of complementary activities for a firm is quite close to the idea of economies of scope, there are formal differences between the two.[3]

The following historical example illustrates the empirical relevance of supermodularity to changes in agriculture. In the broiler industry, new shipping techniques have been developed over the past 40 years, such as ice baths, which increase the distance fresh unfrozen chicken can be shipped. Because consumers as a whole prefer purchasing fresh chicken rather than frozen chicken, the development of these techniques increased processors' returns from the chicken they sold. The broiler industry is also characterized by substantial vertical integration and coordination. Consequently, the same firms that process and sell chicken also purchase or, in some cases, develop their own genetics, thereby influencing broiler carcass traits. Over time, broilers have been bred so that their carcasses absorb less water (Havenstein et al.). This trait reinforces the gains from new shipping technologies, because the reduced carcass water absorption results in a more desirable product after shipping. At the same time, the new shipping methods allow the processor to utilize this carcass trait over a larger fresh chicken market. In other words, the gains from the two practices jointly are larger than the gains from each

[3] For more information on how supermodularity relates to other economic concepts, see Milgrom and Roberts. For more information on the formal conditions under which supermodularity holds, see Milgrom and Shannon. Topkis (1998) summarizes most known results regarding supermodularity, and provides a number of economic and other applications. One source of earlier examples of the use of supermodularity in economic applications is Takayama.

Table 1. Complementarities in the Broiler Industry: Returns from Technology Pairs

Water Absorption by Carcasses	Method of Chilling Carcasses for Transport	
	Ice Baths	Older Transport Approaches
Low	30	22
High	27	20

of them separately. Table 1 uses illustrative numbers to demonstrate this relationship. Supermodularity is reflected in the fact that the sum of the off-diagonal elements is less than the sum of the diagonal elements.

The invention of the mechanical tomato harvester and the breeding of tomato varieties with very narrow maturity windows provide another example of complementary innovations. Without the plant breeding innovation, the mechanical tomato harvester would not have been a technological advance because the harvester destroys the plants. With varieties for which tomatoes all ripen simultaneously, the loss of the tomato plants is not costly. The harvester, on the other hand, increases the profitability of growing varieties that ripen in a narrow maturity window.

Understanding Value Differentiation Using Complementarities

The essential components of agricultural change identified by agribusiness analysts are exactly the components which have proven difficult for economists to articulate and evaluate using standard marginal techniques. Marrying the two literatures, the theory of complementarities as formalized using supermodularity is capable of addressing these changes. Following the orientation of the agribusiness literature, it is based on the observation that production, organization, and management practices tend to occur in clusters. A firm's responses to exogenous changes are mutually reinforcing across these areas, leading to these activity clusters.

Supermodularity captures the intuition of the agribusiness literature that relationships among the observed changes in agriculture are important, and explains why it is difficult to assign causality among them. It also has analytical advantages over more traditional techniques; supermodularity allows comparative statics to be performed in more general settings than a marginal analysis would permit. Following the agricultural economics literature, the value differentiation framework generates testable hypotheses. The framework is developed using a formal hypothesis from Topkis (1995), and its implications are explored for agriculture. Formal definitions and proofs are provided in the appendix.

■ PROPOSITION 1: *Let* $\mathbf{t} \in T$, $\mathbf{x}_s \in X$, *where* T *and* X *are sublattices so that the parameters and non-quality decision variables are each contained in sublattices. Let* $z_s \in Z_s$, *and let* Z_s *be a chain. Let* $p_{s+1,s} \in P_{s+1,s}$, *and let* $P_{s+1,s}$ *be a chain. Let demand* $q(p_{s+1,s}, z_s, \mathbf{t})$ *be increasing in* $(-p_{s+1,s}, z_s, \mathbf{t})$ *and supermodular in* $(p_{s+1,s}, z_s)$. *Let* $p_{s+1,s}m - c(m, z_s, \mathbf{t})$ *be increasing in* m, *and* $c(m, z_s, \mathbf{t})$ *be concave in* m *and submodular in* $(m, z_s, \mathbf{t})$. *Let* $k(z_s, \mathbf{x}_s, \mathbf{t})$ *be submodular in* $(z_s, \mathbf{x}_s, \mathbf{t})$. *Then the following five statements are true:*

- *STATEMENT 1. $\pi_s(p_{s+1,s}, z_s, \mathbf{x}_s, \mathbf{t})$ is supermodular in $(p_{s+1,s}, z_s, \mathbf{x}_s, \mathbf{t})$ when (a) the firm takes $p_{s+1,s}$ as given, and (b) the firm chooses $p_{s+1,s}$.*

- *STATEMENT 2. If all stages $s \in \sigma$ are supermodular, then $\Pi(\mathbf{p}, \mathbf{z}, \mathbf{x}, \mathbf{t})$ is supermodular in $(\mathbf{p}, \mathbf{z}, \mathbf{x}, \mathbf{t})$ when either (a) the firm takes $p_{\bar{s}+1,\bar{s}}$ as given, or (b) the firm chooses $p_{\bar{s}+1,\bar{s}}$, where $\bar{s}$ is the final stage of production engaged in by the firm.*

- *STATEMENT 3. When the firm takes $p_{s+1,s}$ as given, the firm's profit in stage s after optimizing over its decision variables,*

$$\pi_s(p_{s+1,s}, \mathbf{t}) = \max_{z_s \in Z, \mathbf{x}_s \in X} \Pi_s(p_{s+1,s}, z_s, \mathbf{x}_s, \mathbf{t}),$$

  is supermodular in $(p_{s+1,s}, \mathbf{t})$.

- *STATEMENT 4. When $p_{s+1,s}$ is a decision variable for the firm, the firm's profit in stage s after optimizing over its decision variables,*

$$\pi_s(\mathbf{t}) = \max_{z_s \in Z, \mathbf{x}_s \in X, p_{s+1,s} \in P} \Pi_s(p_{s+1,s}, z_s, \mathbf{x}_s, \mathbf{t}),$$

  is supermodular in $\mathbf{t}$.

- *STATEMENT 5. Total profits for the firm after optimizing over its decision variables are supermodular in its parameters.*

The product differentiation variable (z_s) is a chain if any two possible values can be ranked. Intuitively, for this condition to hold, it is necessary to be able to quantify the degree of product differentiation, or otherwise rank the differentiation of product attributes. This may be done, for example, by indexing the degree of specialization for related products, or the number of varying product characteristics as a share of total relevant product characteristics.

The supermodularity of demand in price and differentiation means that decreases in price affect the quantity demanded more when the product is less differentiated, while increases in differentiation affect the quantity demanded more when prices are high, relative to the prices of substitute goods. Intuitively, the own-price elasticity of demand is lower for a more differentiated good. Similarly, the percentage change in demand in response to a given change in differentiation is larger when prices are high than when prices are low. The specification of stage s operating profits, determined by the quantity and degree of differentiation produced, requires it to be in a region of positive operating profits. Operating costs increase at an increasing rate as the amount produced increases, and it is more costly to produce a larger amount of a more differentiated product.

The second cost component may be conceptualized as technology costs that are dependent upon the chosen degree of differentiation but are independent of the amount of product produced: the costs of investing in preference detection technology, attribute determination technology, proprietary research, coordination technology, and integration. The submodularity of technology costs means that the marginal cost of producing a higher differentiation level z_s decreases with increases in the variable technology decisions and the general set of available technology.

Proposition 1 provides an analytical basis for the intuition of the descriptive literature that changes are not only observed together, but are somehow related. The identified activities are complementary. Accordingly, jointly adopting these activities or increasing the level of each will result in a greater increase in profits than the sum of the profits from increasing each activity individually. Further, once a firm has optimally chosen its production technology, product differentiation, and production quantity, increases in the general technology set or consumer preferences will positively affect the returns to all of the complementary activities. Thus, a relatively small shift in an exogenous variable might lead to relatively large changes in the behavior of the firm.

A simple example of such a case is when attribute detection, attribute production, and preference determination each have separate cost functions for each stage of production, and each is characterized by the necessary properties for the relevant variables (Goodhue). Attribute detection and preference determination are affected by the degree of coordination with neighboring stages of production. Each stage, including final consumers, is willing to pay more for the product the more closely it corresponds to the desired attribute bundle. In this case, the chosen amount of preference determination is dependent on the degree of integration between stages s and $s+1$, and the cost of determining preferences. Essentially, this means the more specific the desired product attributes are, the more costly it is to determine what attributes are desired by consumers or by intermediate levels of the food chain. Further, the more specific the attributes, the more expensive it is to determine an additional increment of desired attributes. This point is keenly illustrated by the successful ("Mountain Dew Code Red") and unsuccessful ("New Coke") attempts of food product companies to ascertain consumer preferences and introduce new products which meet these preferences. In both cases, soft drink manufacturers introduced products with new attributes. In the case of "New Coke," Coca-Cola's pre-introduction product testing activities clearly were not sufficient to predict the negative public reaction to the reformulated product.

The attribute detection process may be conceptualized in a similar fashion. The more specialized the good, the more costly it is to determine its initial attribute bundle. For example, it is more costly to determine whether or not produce is organically grown than to determine whether or not it has acceptable levels of blemishes to be sold fresh. Similarly, it is more costly to determine the lysine content of corn intended for livestock feed than to simply purchase commodity grain. Generally, it becomes more and more costly to detect additional product attributes, so that the marginal cost of determining attributes increases with the specificity of the desired attribute bundle.[4] For example, while it is more costly to determine the suitability of strawberries intended for the fresh market than for the frozen market, it is even more difficult to determine which fresh strawberries may be shipped long distances and which are suited only for local sales.

Costly product differentiation occurs at all levels of the production chain. Some products, such as organic produce and free-range chicken, must be differentiated at the production levels. Others, such as cornflakes, are differentiated at the processing and marketing levels. Still other products, such as yellow-skinned chickens, are differentiated at the production, processing, and marketing levels. At the production level, the chickens are fed marigolds to produce a yellow coloration. At the processing level, the chickens are packaged under a brand name. At the marketing level, the yellowness of the chicken

[4] Some product certification processes arguably place the burden of detection on the seller, rather than the buyer. In this case, however, one would expect that the costs of meeting this certification standard are reflected in the price of the product. Further, if the buyer desires products with more specific attributes than those certified, he or she must still invest in additional detection. Consequently, there is a marginal cost the buyer considers when deciding whether or not to change his or her desired input attributes. We thank Ben Hermalin for identifying this case.

is then used as a way to differentiate the brand of chicken. The value differentiation model is consistent with these choices.

The firm must also consider the costs of adopting new technologies which alter its cost parameters. Even when the technologies under consideration are parts of different processes, it may be cheaper to adopt a bundle of technologies rather than to adopt each one independently. For example, calibration costs may be less if technologies are simultaneously changed than if the firm adopts them individually and must recalibrate its production process with each adoption.

Implications of the Value Differentiation Model

The above discussion provides examples of the features one would observe for an agrifood system characterized by complementarities across activities, as specified in Proposition 1. Proposition 1 can be used to make predictions about the behavior of such a system, and its effects on farmers and other economic agents. We also derive predictions related to two common questions about the evolution of agriculture. First, is value differentiation biased against certain levels of the production chain, such as farmers? And second, what factors promote value differentiation in a specific sector?

Firms

Value differentiation implies firms are most profitable if they identify and engage in the entire cluster of complementary activities, because the benefits from engaging in all the complementary activities are greater than the benefits of engaging in any subset of activities. The firm maximizes profits by engaging in the profit-maximizing level of the complementary activities $(q_s, \mathbf{x}_s)$, for all S stages in the profit-maximizing set of stages.

Innovation alone does not guarantee success in value differentiation; if an innovating firm does not engage in all of the complementary activities, it will not fully capture the benefits of its innovation.[5] For example, an agricultural biotechnology firm that develops a pest-resistance trait for a crop will need to determine which production regions have a problem with that pest, and incorporate the trait into germplasm with the appropriate number of days to maturity. In the absence of this preference determination activity, the firm will not utilize its innovation as profitably. It may include the trait in varieties for regions where the pest is not present, so farmers would not pay for the trait; or it may omit the trait in varieties for regions where the pest is present and farmers would pay for the trait.

Similarly, while we have modeled technology as either generally-available technology, or as proprietary research that generates new (complementary) technologies, a third case may sometimes be important. Certain necessary innovations for increasing the level of a specific activity could be patented by another firm. In order to benefit from value differentiation, a firm must be able to *access* intellectual property and other inputs, perhaps by licensing from the patent holder. This suggests intellectual property

[5] The formal argument supporting this statement follows the proof of Prediction 2. Consider a function $f(\mathbf{x})$, where $\mathbf{x}$ is a vector $(x_1, ..., x_n)$. When f is maximized over all n variables, its value is at least as large as when f is optimized over $n - 1$ variables and x_n is fixed at an arbitrary $\bar{x}_n$. Thus, a firm that sets $\bar{x}_n = 0$ when the value of the function is maximized at some $x_n > 0$ will have lower profits than a firm maximizing over all n variables.

can aid in exploiting complementarities, since the innovating firm will be able to control the differentiated product attributes or proprietary technologies derived from its intellectual property. Potentially, an innovator could stifle its opponents' ability to engage in value differentiation by refusing them access to its intellectual property. This possibility is consistent with "anticommons" arguments that patents may unduly restrict innovation (e.g., Heller and Eisenberg). It is also supported by developments in plant biotechnology, where firms hold intellectual property rights to essential gene insertion procedures. Other firms must pay to use these procedures. (Although we do not address inter-firm relationships here, there are clearly numerous strategic considerations affecting licensing decisions for both parties, as there are for all inter-firm decisions.)

Returns to Research

Value differentiation implies returns to research may need to be broadly defined in order to be accurately measured. Research which promotes value differentiation will have benefits above and beyond its direct marginal product. Although it may be difficult to precisely evaluate the contribution of research if other value differentiation-promoting changes are present, it is important to not dismiss these synergies completely when estimating returns to research. These observations are consistent with the attribution difficulties discussed in Alston and Pardey.

Is Value Differentiation Biased in Favor of Certain Levels of the Production Chain?

Modeling the value differentiation process provides insight into some of the policy concerns with respect to value differentiation and associated changes in agriculture, including the increased importance of proprietary intellectual property and increased vertical coordination. At their core, these issues address the possibility that the transformation process may be biased in favor of certain levels of the production chain. This is illustrated by the concern regarding proprietary research which is evident in the descriptive literature and the trade press. Increasingly, these innovations are privately funded and controlled.

One specific hypothesis pertaining to the transformation process can be gleaned from these concerns: It will favor innovators who control the underlying genetic stocks or who conceive new ways of collecting consumer information (Boehlje 1996; Zilberman, Yarkin, and Heiman). A portion of their gains likely comes at the expense of others in the production system. In terms of Proposition 1, these innovators have invested in research and development, ρ, which lowers their costs of engaging in value differentiation.

The model may be used to examine these questions. The basis of the model is a profit-maximizing firm which decides if it will adopt value-differentiating technologies and activities. Firms' decisions across levels of the chain are dependent on one another, in the sense that their alternatives are jointly determined. Statement 5 of Proposition 1 predicts the following regarding which stages will integrate as part of their endogenous response to an exogenous shock or change in production technology decisions.

■ PREDICTION 1. *Firms with a greater degree of value differentiation at their stage(s) of production are more likely to increase their degree of vertical coordination in response to an exogenous shock.*

This prediction emphasizes that supermodularity regards *changes*, rather than levels. Firms that are increasing their share of value added due to an exogenous shock to technology or consumer preferences would be expected to increase their vertical coordination between adjacent stages of the production process, and to use this increased vertical coordination for greater control over product attributes.[6] This prediction is consistent with the pattern of vertical coordination in the California wine grape industry. Sequential logit analysis of coordination choices showed that more differentiated regions exhibited closer coordination between grape growers and vintners (Goodhue et al.). This pattern likely emerged in response to (a subset of) consumers' preferences shifting to favor premium bottled wines with specific characteristics, rather than sweet bulk wines.

Prediction 1 does not directly address the exercise of market power, and its role, if any, in the value differentiation process. Although the model's ability to address market power is limited at best, because it does not include strategic interactions, the following prediction can be made.

■ PREDICTION 2. *Firms exercising market power will receive greater gains from value differentiation than firms not able to exercise market power, ceteris paribus.*

Essentially, this prediction stems from the additional profits a firm may generate by extracting more consumer surplus from its buyers through its pricing choices. In terms of Proposition 1, the firm cannot be worse off when price is a decision variable, rather than exogenous. Competitive firms cannot avail themselves of this opportunity. While a dynamic path for a firm is not modeled, Prediction 2 suggests firms with market power in an initially undifferentiated sector will have more returns to invest in new technologies as they become available than firms without market power. Such differences could result in alternative value differentiation activity choices being associated with the presence or absence of market power for a firm.

Predictions 1 and 2 raise another, related question: What is the effect of increased value differentiation at stage s for stage $s+1$? When the two stages are controlled by the same firm, Proposition 1 implies an increase in an exogenous variable which increases value differentiation in the upstream stage will increase value differentiation in the downstream stage controlled by that firm. Similarly, it implies an increase in an exogenous variable which increases value differentiation in the downstream stage will increase value differentiation in the upstream stage controlled by that firm. For example, selective breeding may result in cattle that consistently grade higher on average compared to cattle from other genetic lines. For a packer controlling these cattle, this innovation

[6] Note that the analysis identifies the relationship between vertical coordination and the value differentiation process; it is not intended to explain every case of the ownership of different, even adjacent, stages of the production chain by a single firm for other reasons. Ownership of multiple stages of the production chain is not sufficient evidence for the existence of the complementary activities comprising the value differentiation process. Also, we do not address strategic issues arising from increased vertical coordination between two stages initially controlled by different firms. Strategic factors may influence the ultimate form of inter-firm coordination.

increases the value of introducing a product line for supermarkets intended to emphasize the greater consistency and higher quality of their meat. On the other hand, if consumers' willingness to pay for a high-quality, consistent steak increases, the value to a packer of introducing such a product increases, as does the value of developing a pool of feeder calves with the genetics to support it.

Unfortunately, the ultimate effect is unclear when the two stages are not controlled by the same firm through integration or coordination, although some comments can be made. Clearly, the price at which stage $s+1$ purchases its input ($p_{s+1,s}$) increases when the increase in value differentiation is due to a shift in consumer preferences (τ). When the change is due to a change in general technology (ξ), the effect on price will depend on the effect on costs and the competitive conditions in the relevant markets. Increased value differentiation, regardless of its cause, will tend to increase the value to stage s of more closely coordinating with stage $s+1$. This increased value may prompt stage s to acquire firms in stage $s+1$, initiate contracting, or take other observable actions to increase coordination between the stages. A similar argument holds for stages $s-1$ and s.

Which Factors Promote Value Differentiation?

There are two sources of exogenous change: (*a*) consumer preferences and (*b*) generally-available technology. In the descriptive literature, both of these forces are predicted to enhance value differentiation, leading to a higher value of z_s and more vertical integration. Structuring the profit function as supermodular allows the model to be used to identify conditions under which this will be true, as established in Statement 5 of Proposition 1.

The prediction of the descriptive literature will be true when exogenous changes increase the marginal returns of the complementary activities, including quality detection, preference detection, quality production, research, and integration. One such exogenous change is the rise in the number of two-career and single-parent homes. These lifestyle changes are perceived to have led consumers to emphasize convenience and ease of preparation in their food choices. These exogenous changes in preferences have led to greater value differentiation, as purchases of basic foodstuffs have been replaced by partially or fully prepared foods and entire meals. Consumers' increased emphasis on convenience appears to increase the marginal product of the activities in the value differentiation process.

Biotechnology and information technology are commonly viewed as exogenous forces which will increase the marginal returns to the activities in the value differentiation process, much like the changes in consumer lifestyles discussed above. The effects of these technologies depend, however, on their applications. Biotechnology innovations such as Bt corn and cotton are designed to reduce production costs rather than to aid in tailoring product attributes. The effects of such cost-oriented innovations on the progress of value differentiation are a priori unknown. These products may simply lower the cost of producing a commodity with little differentiation, and not affect quality and the value differentiation process. Alternatively, consumer refusals to use bioengineered products, such as the European Union's ban on Roundup Ready soybeans, may indirectly aid value differentiation in oilseeds and grains by forcing the creation of methods to maintain product identity at each stage of the production chain.

Potentially, these products may slow the value differentiation process for two reasons. First, the bioengineered products may reduce the cost of producing a specified attribute bundle $\bar{z}_s$, but not reduce the cost of producing a more differentiated product. Accordingly, the marginal cost of producing $\tilde{z}_s > \bar{z}_s$ is increased by the reduction in production costs for $\bar{z}_s$ due to the innovation. This marginal cost increase may cause such bioengineered products to slow value differentiation. Similarly, if biotechnology results in a more homogeneous product at the production level, the marginal benefit of improving attribute detection may be reduced. Consequently, an increase in available biotechnology does not result in an increase in the marginal returns to all of the complementary activities. In this case, innovation does not necessarily further value differentiation.

Formally modeling the value differentiation process allows the predictions of the descriptive literature regarding the effects of exogenous changes to be clarified. The forces identified as promoting value differentiation may not do so. The predictions of the descriptive literature are overly broad. The model demonstrates the importance of recognizing the interaction between an outside force and value differentiation before predicting its effect. In particular, cost-reducing innovations often do not contribute to value differentiation.

- PREDICTION 3. *Not all exogenous changes in technology and consumer preferences will further the value differentiation process. Value differentiation will only be advanced when an exogenous change increases the marginal returns of the component complementary activities, including preference determination, attribute detection, attribute production, and coordination.*

What the model cannot do in this reduced form is to predict the precise outcome of a particular exogenous change. The exact magnitude of its impact is dependent upon the structural forms underlying this reduced-form model. By using supermodularity, however, we can characterize conditions under which the direction of these changes can be predicted. Of course, this limitation is a general characteristic of theoretical models.

Testing the Implications of Value Differentiation

In order to test the relationships in the value differentiation model directly and comprehensively, detailed information is required. A test for the existence of complementarities across all components of the value differentiation framework would require firm-level data containing information on profits, product differentiation, attribute detection activities, preference determination activities, coordination, and other variables affecting firm profits. Because direct information regarding these activities is not normally maintained as part of a firm's record-keeping process, a researcher would need to collect her own data. Further, much of this information is proprietary, and inducing firms to cooperate is likely to be quite difficult.

One way to approach testing is to follow a quantitative case study approach such as the one used by Ghemawat. Rather than limit his quantitative analysis to econometric methods, he incorporates a variety of approaches, such as actual calculations conducted by a firm prior to making a decision, simulations, and non-econometric probability analyses. Many of the studies reviewed by Masten use similar tools. Such an approach may prove particularly valuable when conventional econometric data sets are difficult or impossible to collect. Ghemawat also emphasizes an important point: While direct interviews with managers may reflect personal biases, they can also provide valuable information that cannot be obtained through other means. Even when econometric techniques can be used, alternative quantitative techniques and interviews can greatly enhance an analysis. The robustness of one's findings can be evaluated by examining whether they are consistent across techniques and data types.

Testing can also be conducted using econometric techniques. If enough data were collected to estimate a structural model, the testing procedures developed in Athey and Stern could be employed. If only a reduced-form model could be estimated, two estimation procedures could be used. The first examines the sign of correlations across ordinary least squares (OLS) residuals. Positive correlations are interpreted as evidence of complementarity. Arora and Gambardella, and Graff, Rausser, and Small adopt this approach to examine coordination choices by individual firms in the pharmaceutical and agricultural biotechnology industries, respectively. The second estimation procedure evaluates interaction effects in OLS or two-stage least squares (2SLS) regressions using dummy variables for the possible combinations of the complementary activities, as in Ichniowski, Shaw, and Prennushi.

Collection of such a data set poses its own difficulties, due to the quantity and detail of information required. As noted earlier, proprietary data are difficult to collect. Ensuring adequate participation by firms may be difficult. While some choices may be easily countable or otherwise quantifiable (such as patent counts in Graff, Rausser, and Small), calibrating activity choices across firms on a common scale requires extensive industry knowledge, as well as examination of the effects of the calibration on econometric outcomes.

One means of correcting for this difficulty is to use dummy variables to describe different firm activity choices. Another is to construct an index, or scaling algorithm. Ichniowski, Shaw, and Prennushi employed both of these procedures. Clearly, when collecting data, it is desirable to create countable variables—such as the number of specific product attributes—as a measure of differentiation. For example, differentiation of specific consumer products could be measured by the number of governmental labels for which a given product qualifies (organic, low-fat, etc.), nutritional content, and advertising expenditures.

Data collection within a single commodity or group of closely related commodities, ideally with the cooperation of relevant industry groups, would help mitigate these problems. This procedure was followed by Ichniowski, Shaw, and Prennushi for human resources management practices in steel finishing lines. Focusing on a single firm type, such as food retailers, might also aid in mitigating these problems, but may introduce additional difficulties, such as the inadvertent exclusion of non-retailer firms moving into traditional retailer functions, perhaps due to value differentiation. It may also be possible to collect sufficient time-series data regarding a single firm to allow testing.

While a complete test of the assumptions of the value differentiation model cannot be conducted with current secondary public data, it may prove possible to test the complementarity of individual relationships using data collected for other purposes. For example, data collected in order to investigate the competitive implications of increased vertical coordination in the livestock industry may contain information pertaining to attribute detection activities by packers as well.

Of course, the nature of a complementary process may influence estimates of complementarities by introducing a selection bias; e.g., relatively few firms would be expected to adopt only one of two complementary activities. More importantly for our purposes, reduced-form procedures could not disentangle whether the two activities were directly complementary, or indirectly complementary through a third activity or explanatory variable for which data are not available. Arora proposes the use of structural restrictions to address the latter problem. While the restrictions are simple in the two-activity case, a variant of the approach may also be used for more than two activities. In this case, restrictions with respect to the cross-derivatives of complementary activities and other explanatory variables for firm profits must be imposed. Provided these limitations of the available estimation procedures are kept in mind, it may be possible to test some implications of the value differentiation model using existing data.

Conclusion

Value differentiation is characterized by complementarities across activities that aid firms in identifying desired products and delivering these products to consumers at the lowest possible cost. These complementarities explain sometimes dramatic responses to relatively small exogenous changes in technologies and tastes. This model of value differentiation incorporates the insights of the descriptive literature into an analytical framework, allowing researchers to assess the extent of value differentiation in a given product, and provide qualitative predictions. In the previous section, potential means of testing the model and its predictions, and associated pitfalls were discussed.

Formalizing the observations of the descriptive literature using supermodularity provides a model which is reduced-form but nonetheless has some predictive power, and hence provides testable hypotheses. Proposition 1, Statement 5, which is restated as Prediction 3, shows that exogenous shocks which increase the marginal values of the core value differentiation components will have a favorable effect on value differentiation. While technological innovations that reduce the costs of unit production may benefit their inventors, users, and others, their effect on the value differentiation process is determined by how they affect firms' decisions regarding these processes—not by their effect on the cost of producing units of a given degree of differentiation. The value differentiation framework allows for an integrated evaluation of the factors affecting firms' decisions.

The model's predictive power is conditional upon exogenous shocks. Given a shock or the absence of a shock, the model can describe the firm's behavior. The model cannot predict the timing and nature of an uncontrollable exogenous shock the firm may sustain. Given its parameters, a firm that begins to transform can do so very rapidly, resulting in a revolutionary rather than an evolutionary change in its behavior. A relatively small exogenous shock can induce relatively large changes in firms' activity choices, due to these complementarities.

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Appendix: Definitions and Proofs

Definitions

A *sublattice* may be defined as follows. A set X is a partially ordered set if it is a set with a reflexive, antisymmetric, and transitive binary relation ($\leq$). For any two elements of X, x_1 and x_2, their least upper bound (if it exists) is called their *join*. Their greatest lower bound is called their *meet*. A partially ordered set is a *lattice* if it contains the meet and join for all possible pairs of elements. If X is a lattice, and S is a subset of X, S is a sublattice of X if it contains the meet and join for every pair s_1, $s_2 \in S$. A *chain* may be defined as follows. If $X \subseteq \Re^n$, and if $\mathbf{x} \in X$ and $\mathbf{x}' \in X$ imply that either $\mathbf{x} \leq \mathbf{x}'$ or $\mathbf{x}' \leq \mathbf{x}$, then X is a chain.

- *PROOF OF PROPOSITION 1.* Statements 1, 3, and 4 of Proposition 1 are direct applications of theorem 3.5 in Topkis (1995). Statements 2 and 5 hold because the sum of supermodular functions is supermodular [property proved in Topkis (1978)].

- *PROOF OF PREDICTION 1.* The proof follows directly from the application of supermodularity to the complementary activities in the value differentiation process in Proposition 1. Vertical integration and differentiation are complementary activities at stage s. That is, stage s profits are supermodular in these decision variables. Hence, increase in these activities should be observed together.

- *PROOF OF PREDICTION 2.* Consider a function $f(x_1, ..., x_n)$. The maximum value of f when x_n is fixed at $\bar{x}_n$, and $n - 1$ variables are chosen, cannot be larger than the maximum value of f when the constraint $x_n = \bar{x}_n$ is removed, and f is maximized over all n variables. Equivalently,

$$\underset{x_1,...,x_n}{\operatorname{argmax}} f(x_1, ..., x_n) \geq \underset{x_1,...,x_{n-1}}{\operatorname{argmax}} f(x_1, ..., x_{n-1}; \bar{x}_n).$$

- *PROOF OF PREDICTION 3.* Prediction 3 corresponds directly to Statement 5 in Proposition 1.