

Genetic Information in Agricultural Productivity and Product Development

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Abstract

A prominent facet of recent changes in agriculture has been the advent of precision breeding techniques. Another has been an increase in the level of information inputs and outputs associated with agricultural production. This paper identifies ways in which these features may complement in expanding the variety of processed products, the level of productivity, and the rate of change in productivity. Using a martingale concept of “more information,” we identify conditions under which more information increases the incentives to invest and engage in product differentiation. A theory on how genetic uniformity can enhance the rate of learning through process experimentation, and so the rate of technical change, is also developed.

Keywords: experimentation, genetics, information, martingale, sorting, uniformity, value added.

JEL: D2, O3, L0, N5

GENETIC INFORMATION IN AGRICULTURAL PRODUCTIVITY AND PRODUCT DEVELOPMENT

Two of the most important economic innovations over the past half-century have been the ability to store and process large amounts of data and the development of techniques that modify life forms to meet specific ends. In agriculture, the latter has been a significant factor in productivity growth for both the crop and livestock sectors. The effects of innovations in information technology on production agriculture have been far more limited. Whereas product innovation and differentiation have been identified as the avenues to success by most industrial firms, production agriculture has continued down its path of producing low-cost commodities. History has shown that the keys to success in a commodity market are expansion to capture scale economies and specialization to adopt cost-reducing technologies more rapidly. Returns to managing information in commodity markets have arisen mainly from cost-saving applications in processing and distribution rather than from developing production systems that tailor production to consumer demand.

While the technical capacity to focus on addressing consumer demands now exists, consumer demands for variety generally have not yet been met. Neither have consumer and processor demands for information about on-farm activities. For example, recalls of potentially contaminated meat have been far larger than they would have been had a food traceability system been in place. And efforts to improve beef quality have been impeded by the lack of information about the genetic traits of cattle and the production practices of heterogeneous producers (Boleman et al. 1997; Miller et al. 2001; National Cattlemen's Association 1994, 1995).

If production agriculture is to have a future in producing inputs with desired traits—be they genetic or non-genetic such as knowledge about the animal welfare practice used to produce a given piece of meat—then new investments in information technology and genetics must take place. The intent of this paper is to develop an

understanding of the mechanisms by which genetics and information interact in determining commercial decisions.

We focus first on the return from information about input attributes that a processor can use to increase the likelihood that value-added processing will be successful. Currently, consumers are demanding products that are more convenient and a consistent consumption experience (Ulrich and Brewin 1999; Ferrier 2002). In order to remain competitive, processors must add further value to meet the demands of restaurants and domestic consumers. Processors will attempt to differentiate their product only if they know that the raw material they purchase from farmers will perform reliably during processing. We develop a model that characterizes how information plays a role in the decision to develop new markets for product derivatives. As technical attributes of the raw material become more certain, the material can be better sorted to improve uniformity. This makes it optimal to engage in more product differentiation. We illustrate the model with reference to soybean crops through the twentieth century.

We then turn to an exploration of how management efficiencies can also arise from information on the nature of raw materials. We demonstrate how *ex ante* sorting to obtain homogeneous lots of raw materials increases the information content of experiments in production because controlled experiments provide less noisy results. Thus, the returns from experimentation increase, which leads to more production and processing experiments. We provide evidence to show that this learning story is consistent with events in the U.S. poultry and hog sectors over the past 70 years.¹

Our two modeling frameworks lend support to the notion that the keys to an agricultural sector that delivers inexpensive, differentiated inputs to processors who use them to meet new consumer demands are a strong knowledge base concerning genetics, the capacity to cheaply sort production into homogeneous lots, and a highly controlled production/processing environment. Concerning the latter, a low age at slaughter permits a more controlled production environment, and so, the theory predicts, poultry products should more readily meet consumer demands than beef or even pork products. Finally, we suggest that cloning and other technologies that promote uniformity in raw materials may have a profound impact on commercial animal agriculture.

Information and Value-Adding Activities

A processor buys raw material from farmers and has the choice of transforming it into either a standard product, A, which generates unit revenue P with certainty, or an alternative product, B, which is novel. The standard product uses technology that is well tried and tested. This does not mean that there is not significant variation in the standard (commodity) product but rather that the technology is less specific and more flexible in adapting to variations. For example, the technology may be more labor intensive, in which case human intervention can better accommodate variation.

The novel product generates unit revenue, net of additional costs, amounting to $P + \delta$ if all goes as planned. However, because of inconsistent input attributes, there is a risk that the product does not turn out as planned and a loss is incurred. We identify the loss as $L \in \mathbb{R}_+$ and capture the risk of this loss by the true loss probability $\omega_\infty(K) \in (0, 1)$, where the choice of the subscripted infinity symbol will be explained shortly. As suggested by the notation, this loss probability can be altered by an investment, the level of which is represented as $K \in \mathbb{R}_+$. While the loss, if it occurs, is not random, the loss probability is a random variable because it depends upon product attributes—such as genetics—and the processor of any given lot of raw materials is incompletely informed about these attributes.

In presenting our model of how information affects decisions, we first consider an environment in which the processor is fully informed about the determinants of $\omega_\infty(K)$, where these determinants can be observed and where sorting incurs no costs. This information is used to sort product into that which is processed and that which is not. For a given K , the true distribution of product reliability is $H_\infty[\omega_\infty(K)]$. Assuming risk neutrality, or assuming large numbers of units of raw materials and appealing to the Glivenko-Cantelli theorem (Durrett 1996, p. 59), expected product revenue reflects the processor's benefit function. Under the standard product, the expected benefit is P . Under the novel product and full information, the expected benefit from processing a lot of input is $P + \delta - L \omega_\infty(K)$. Therefore, $\omega_\infty(K) = \delta/L$ is the cutoff point such that a unit with $\omega_\infty(K) < (>) \delta/L$ should (should not) be subjected to novel processes. The cutoff

point is independent of the value of K , although the fraction of raw material that is processed is not.

The added value to the fully informed processor of sorting raw materials, relative to the base of not allocating any raw materials to the production of novel product B, is

$$V(K) = \int \max[0, \delta - L\omega_\infty(K)] dH_\infty[\omega_\infty(K)], \quad (1)$$

where fraction $H_\infty[\delta/L]$ is processed and fraction $1 - H_\infty[\delta/L]$ is not.

To capture the concept of being “more informed” about processing and about the nature of the inputs used, we will apply the notion of a martingale process.² We start with the baseline empty information set, $\mathcal{F}_0(K) = \emptyset \forall K \in \mathbb{R}_+$, which gives rise to a K -conditioned reliability assessment random variable, $\omega_0(K)$. This baseline empty information set is “observation unconditional” in the sense that one learns nothing new from observing the raw material. And the observation unconditionality is true regardless of the level of investment chosen. The observation unconditional random variable has the distribution function $H_0[\omega_0(K)]$.

A strictly larger information set $\mathcal{F}_1(K) \supset \mathcal{F}_0(K)$ gives rise to the $\mathcal{F}_1(K)$ -conditioned reliability assessment random variable $\omega_1(K)$. Continuing, we may conceive of a sequence, possibly countably infinite, of increasingly informed environments $\{\mathcal{F}_i(K)\}_{i=0}^{i \leq \infty}$ where $\mathcal{F}_0(K) \subset \mathcal{F}_1(K) \subset \dots \subset \mathcal{F}_i(K) \subset \dots \subset \mathcal{F}_\infty(K)$ and each is a σ -algebra.³ Such a collection of information sets is called a filtration. The sense in which $\mathcal{F}_i(K) \subset \mathcal{F}_{i+1}(K)$ merits pause for thought. One might think of a filtration as a set of documents that might accompany raw materials. Document $\mathcal{F}_0(K)$ reveals no information about the material, and document $\mathcal{F}_1(K)$ reveals one relevant piece of information. Continuing, document $\mathcal{F}_i(K)$, $i \in \{1, 2, \dots\}$ reveals one additional conditionally independent relevant piece of information over that contained in $\mathcal{F}_{i-1}(K)$.⁴

Suppose, for example, a coin was flipped three times in sequence with outcomes $A_1 \in \{0, 1\}$, $A_2 \in \{0, 1\}$, and $A_3 \in \{0, 1\}$. Ignoring the investment level, we might define the space of events on the first toss as $\mathcal{F}_1 = \{\{0\}, \{1\}\}$, the event space on the first two

tosses as $\mathcal{F}_2 = \{ \{0, 0\}, \{0, 1\}, \{1, 0\}, \{1, 1\} \}$, and the event space on the first three tosses as $\mathcal{F}_3 = \{ \{0, 0, 0\}, \{0, 0, 1\}, \{0, 1, 0\}, \{0, 1, 1\}, \{1, 0, 0\}, \{1, 0, 1\}, \{1, 1, 0\}, \{1, 1, 1\} \}$. We have that $\mathcal{F}_1 \subset \mathcal{F}_2 \subset \mathcal{F}_3$ in the sense that the more inclusive set fills out information on events in the largest event space.

In our study of reliability, we associate with the filtration a sequence of random variables $\{\omega_i(K)\}_{i=0}^{i \leq \infty}$ where $\omega_i(K) \in (0, 1)$ is the expected reliability when conditioned on events captured in $\mathcal{F}_i(K)$. For each K , the largest information set, $\mathcal{F}_\infty(K)$, contains all relevant information. To avoid the possibility of confusion at a later juncture, we distinguish between the ordinal size of the information set at a given level of K and the level of K by defining the i th largest information set as $\{i\}$ rather than $\mathcal{F}_i(K)$. Using this notation, if one knows which of the events in $\{\infty\}$ has occurred then one knows the true value of the reliability parameter, that is, of $\omega_\infty(K)$.

Expectations with respect to $H_0[\omega_0(K)]$ (i.e., unconditional expectations) are denoted by $E[\cdot | \mathcal{F}_0(K)]$ or $E[\cdot]$ and, in general, expectations conditioned on events that are specified in $\mathcal{F}_i(K)$ are represented by $E[\cdot | \mathcal{F}_i(K)]$. We make the following:

ASSUMPTION 1. $\omega_0(K) = E[\omega_\infty(K)] \geq \delta/L \forall K \in \mathbb{R}_+$.

Viewing equation (1), this assumption states that, irrespective of the level of investment, it is rational not to subject any raw materials to novel technology B when $\mathcal{F}_0(K) = \emptyset \forall K \in \mathbb{R}_+$. The equality in the assumption warrants some explanation in that it imposes the martingale property. If

$$E[\omega_\infty(K) | \mathcal{F}_i(K)] = E[\omega_j(K) | \mathcal{F}_i(K)] = \omega_i(K) \forall i, \forall K \in \mathbb{R}_+, \forall j \geq i, \quad (2)$$

then the process of K -conditioned random variables represented by $\omega_i(K)$ is said to be a martingale with respect to the filtration.^{5,6} Henceforth we will also suppose the following:

ASSUMPTION 2. For a given level of investment K , random variables $\{\omega_i(K)\}_{i=0}^{i \leq \infty}$ follow a martingale process in the manner of equation (2).

EXAMPLE 1. Let $\xi_i, i \in \{1, 2, \dots, N\}$, be a sequence of independent random variables with bounded support and mean zero. Then $S_n = \sum_{i=1}^n \xi_i$ is a martingale where each \mathcal{F}_i is given by the event space for $\{\xi_1, \xi_2, \dots, \xi_i\}$.

EXAMPLE 2. The standard Wiener process generated from integrating across infinitesimal normal innovations underpins much of real and financial option theory. It is a (continuous) martingale (Trigeorgis 1996) with the appropriately defined filtration. However, since a normal distribution does not have a bounded support, we could not use this form of martingale to model our knowledge on reliability parameters.

EXAMPLE 3. Let $\xi_i, i \in \{1, 2, \dots, N\}$ be a sequence of random variables with bounded support. Define $\eta_i = \xi_i - E[\xi_i | \xi_1, \xi_2, \dots, \xi_{i-1}]$, $i \in \{2, 3, \dots, N\}$, and $\eta_1 = \xi_1$. Then $S_n = \sum_{i=1}^n \eta_i$ is a martingale where the \mathcal{F}_i are of the form given in Example 1.

To be clear about how we intend to apply the martingale property, start with the environment where the stock of heterogeneous raw materials available to the processor is fixed so there is no randomness in the true mass distribution of raw materials. What is random is the perceived level of reliability. As the processor becomes more informed about the nature of the raw materials, this randomness converts to observed heterogeneity in the stock, that is, to known variability. In an environment where there is known variability, it is possible, at least conceptually, to sort, *ex post*, the raw materials.⁷

Each $\omega_i(K)$ has associated with it an absolutely continuous measure, $H_i[\omega_i(K)]$, where we clarify our concept of information as an extension of a σ -algebra:

DEFINITION 1. Make Assumption 2 given previously. Distribution $H_i[\omega_i(K)]$ is said to be more informative than $H_j[\omega_j(K)]$ whenever $i \geq j$.

There exists an intimate relationship between the martingale structure and the concept of a mean-preserving spread (Rothschild and Stiglitz 1970). Specifically, if $E[\omega_i(K) | \omega_j(K)] = \omega_j(K) \forall i \geq j$, then $H_i[\omega_i(K)]$ is more dispersed than $H_j[\omega_j(K)]$ in the sense of a mean-preserving spread. Thus, $H_i[\omega_i(K)]$ is more informative than $H_j[\omega_j(K)]$ because some noise has been explained and incorporated into the information set.

Other economic concepts of information order exist. Chambers and Quiggin (2001) apply duality and set theory to model information in an Arrow-Debreu state-contingent framework. Athey and Levin (2001) use measure theory to provide an exact notion for “more information” that pertains in the case of optimization problems with some specified analytic structure. While their approach is applicable to our problem, we choose not to use it here because the stochastic attributes of the approach are not as well explored as the martingale concept by which we will characterize “more information.” In game theory, the standard approach to modeling more information employs the Markov process (Fudenberg and Tirole 1991). In it, all probabilities of a future event are held to depend only on the present state and not on past states of nature. Because the probability density function is completely described, this Markov condition is more imposing than the martingale condition as given in equation (2). Our analysis does not require this level of structure, and so we do not impose it.

Returning to equation (1), in imperfectly informed environments we may write

$$V[\mathcal{F}_i(K)] = E [\text{Max}[0, \delta - LE[\omega_\infty(k)]]] = E [\text{Max}[0, \delta - L\omega_i(k)]]. \quad (3)$$

This expression reflects the value of more information on the nature of the product. More information may make it a good bet to allocate some of the raw materials to novel product B and thus access some surplus relative to the standard product, A.

Now, by the convexity of the $\max[\cdot, \cdot]$ statement, Jensen’s inequality, and the observation that

$$E [\max[0, \delta - LE[\omega_\infty(K) | \mathcal{F}_i(K)]]] = E [\max[0, \delta - LE[E[\omega_\infty(K) | \mathcal{F}_{i+1}(K)] | \mathcal{F}_i(K)]]]$$

$$\begin{aligned} &\leq E[E[\max[0, \delta - LE[\omega_\infty(K) | \mathcal{F}_{i+1}(K)]] | \mathcal{F}_i(K)]] \\ &= E[\max[0, \delta - LE[\omega_\infty(K) | \mathcal{F}_{i+1}(K)]]], \end{aligned}$$

we have⁸

$$V[\mathcal{F}_\infty(K)] \geq \dots \geq V[\mathcal{F}_i(K)] \geq \dots \geq V[\mathcal{F}_1(K)] \geq V[\mathcal{F}_0(K)]. \quad (4)$$

To interpret the inequalities, we make the following:⁹

ASSUMPTION 3. Sorting is costless.

Consider now the situation where no additional information becomes available to the processor. So $\{0\}$ is the pertinent information set, and we may write

$$V[\mathcal{F}_0(K)] = E[\max[0, \delta - LE[\omega_\infty(K) | \mathcal{F}_0(K)]]] = \max[0, \delta - L\omega_0(K)] = 0, \quad (5)$$

where the last equality is due to Assumption 1. Consequently, no product differentiation occurs. A larger information set, in providing opportunities to condition expectations, allows an expansion of the capacity to sort product. In a concrete setting, more information allows for *ex post* sorting of product. Somewhat more abstractly, more information on genetic composition may allow for better *ex ante* sorting. In these contexts, “more information” may be viewed as a transformation of uncertainty to known variability, and the rational processor will make best use of the known variability by sorting product into that which will be subjected to the novel process and that which will not. In the manner of type I and type II errors, the additional information allows for two kinds of efficiencies. The information makes less likely the event that product allocated to use B fails during processing while the information also makes less likely the event that product allocated to use A was actually of the quality that should have been allocated to use B. It is the action of sorting that underpins relation (4), and it may be encapsulated as follows:

PROPOSITION 1. *The value of a given level of investment increases as the processor becomes more informed in the sense of Definition 1.*

The result does not, however, provide insight into the incentive to increase the level of investment. In fact, it cannot do so because the problem has insufficient structure. We will now place sufficient structure on the problem. Notice that the $\max[\cdot, \cdot]$ statement in equation (3) is decreasing and convex in the random variable. Hence, the marginal product of investment K on the part of the processor, and for a given information set $\mathcal{F}_i(K)$, is positive if an increase in K induces a second-degree stochastically dominated shift in $H_i[\omega_i(K)]$. For the same stock of raw materials, if an increase in K induces such a stochastic shift, then c will tend to be lower and less dispersed at higher values of K .

To summarize the structure that we have imposed on the random variable $\omega_i(K)$, observe that it is ordered in two dimensions. The martingale orders it by the second ordinate in $(K, \{i\})$ while stochastic dominance orders it by the first ordinate in the ordered pair. We have not yet imposed any structure on how the two ordinates might interact. We can now adapt to our context a concept attributable to Topkis (1978).

DEFINITION 2. (Topkis 1978) Let $K \in \mathbb{R}$ and let T be a partially ordered set with order relation \geq_* . Function $G(K, t) : \mathbb{R} \times T \rightarrow \mathbb{R}$ is said to have increasing differences in (K, t) if, for $t' \geq_* t$, it holds that $G(K, t') - G(K, t)$ is monotone nondecreasing in K .

Observe that the filtration is totally ordered by inclusion relation \subset , and so it is partially ordered by that relation. Note too that if, as will be the case, the property of increasing differences is required of a function defined on $(K, \{i\})$, then structure will be imposed on how coordinate interactions affect the function value.¹⁰

RESULT 1. (Topkis 1978) For any sets $S \subset \mathbb{R}$ and $S' \subset \mathbb{R}$, define the partial ordering

$S \overset{r}{\leq} S'$ as the relation whereby $\inf\{S\} \leq \inf\{S'\}$ and $\sup\{S\} \leq \sup\{S'\}$. If

$G(K, t) : \mathbb{R} \times T \rightarrow \mathbb{R}$ has increasing differences in (K, t) then

$\arg \max_K G(K, t) \overset{r}{\leq} \arg \max_K G(K, t') \forall t' \geq_* t$.

Without imposing much structure on the problem, the result basically relates that the optimal values of K are weakly increasing in the value of t . And so, with $M[\mathcal{F}_i(K)] = V[\mathcal{F}_i(K)] - K$ as the processor's objective to be maximized, Result 1 implies the following:

PROPOSITION 2. *Let K induce a second-degree stochastically dominated shift in any given $H_i[\omega_i(K)]$, and let $V[\mathcal{F}_j(K)] - V[\mathcal{F}_i(K)]$ be monotone nondecreasing in $K \forall i \leq j$. Then the optimal level of investment increases in the sense of $\overset{r}{\leq}$ as the firm becomes more informed.*

Proposition 2 is consistent with Chandler's (1992) argument that, in order to justify the capital investment, a firm has to be able to more closely monitor throughput in capital-intensive industries. We will return to the issue of throughput later. Notice, we do not actually need the second-degree stochastic partial ordering on distributions to apply Result 1. Its only role is to ensure that expected marginal product is positive.

One may wonder how investment and product differentiation activities interrelate. To address this issue, we first need to know what the direct role of more information is on product differentiation activities.¹¹

PROPOSITION 3. *There exists an information set $\{i\}^*$, possibly $\{\infty\}$ or $\{0\}$, such that*

- a. All larger sets in the filtration will be associated with the production of both standard product A and novel product B;*
- b. All smaller sets in the filtration will be associated with the production of just standard product A.*

Proposition 3 does not assume increasing differences. But, taken together, that is, under the assumptions in Proposition 2, it can be seen that more information drives both higher investment and product differentiation.¹² Consequently, we can identify two reasons why one might expect more high-value products from processors that are well informed. First, they are better at sorting raw materials. Second, if the increasing

differences property holds, then the comparative advantage at sorting converts to a stronger incentive to upgrade the firm's investment so that it can better glean value-added product from the given raw materials base.

Part (a) of Proposition 3 often may only identify a restricted equilibrium. *Ex post* sorting of product to ensure reliability is costly. It may be possible to substitute these transactions costs for lower *ex ante* sorting transactions costs if the pertinent information is available to breed for homogeneous raw materials. If the differentiated product proves profitable under high *ex post* sorting costs, then optimizing firms may be reassured about the prospects of allocating resources for seeking an *ex ante* solution. The information that allowed for the *ex post* sorting solution surely will be of assistance in developing an *ex ante* sorting solution.

Propositions 2 and 3 bear contrasting with the analysis in Hennessy 1996, where a downstream operator uses the spot market to assess and then purchase product from a producer. Grading errors blur the mean return on a given level of investment for the producer, and thus the producer-level incentives to make an investment that would upgrade the quality of product (i.e., raw material going into processing) are not clear. In that context, the problem was one of asymmetric information in that the producer knew the production practices in place whereas the processor only had available quality assessments through information discernible on the spot market. Vertical integration would solve the problem by removing the information asymmetry, as would *ex ante* contracts with sufficiently high-powered incentives structures, as Bogetoft and Olesen (2003) pointed out.

In our model, there need not be information asymmetry. But the problem and consequences are similar. If we model a lower state of knowledge about the raw materials coming from farms as a shift $\{i + 1\} \rightarrow \{i\}$ along the filtration, then the processor receives a less informative signal. By Proposition 3, less product differentiation will tend to occur as a result, and the processor will not be in a position to reward the growers of highly processable raw materials. Consequently, producer incentives to invest in providing highly processable raw materials will decline. Both the producer and the processor may be caught in a rut of low investment. The point to bear in mind is that, in our model, the information conveyed by the grower to the processor is integrally embedded as part of the

raw materials. The more information the grower can credibly provide, the larger the realized reward likely will be when surplus from processing is divided and distributed back. The spot market is not a good institution for credibly conveying information on raw materials, and so our model would suggest that processors seeking to add considerable value to raw materials are more likely to use direct procurement channels than are processors focused on undifferentiated products.

Case Study: Soybean Product Development

Arguably, soybean has been the most aggressively developed field crop through the twentieth century. While soybean products have comprised part of the staple diet in East Asia since ancient times, demand elsewhere did not become significant until around 1908 when an English firm speculated on developing products for sale to diabetics. However, the “killer application” proved to be crusher-extracted oil for soaps, with by-product cake and meal sold as a protein supplement for animal feed (Piper and Morse 1923). Between 1910 and 1920, and after extensive product research, soap and paint manufacturers propelled a growing demand for the crop.

Until the 1930s, extraction processes left the meal contaminated by residues so that uses in human foods were precluded. Then innovations in extraction allowed for the development of soy flour as an ingredient in such items as ice creams, candies, breads, confectionaries, and prepared mixes (Windish 1981, p. 99). At about this time, too, industrial uses of crop products began to languish, as they were being replaced by petroleum derivatives. Comparatively, soybean products performed inconsistently and were more susceptible to contamination (Myers 1994; Hammond 1995).

Nonetheless, crop utilization had gained traction in feed and food markets. Global soybean production grew from 12 million tons, mostly in China, in the mid-1930s to surpass 100 million tons in the late 1980s with the majority being harvested in the United States. (den Boer 1991). Product and varietal development programs underpinned the growth in U.S. production and global consumption (Windish 1981). Being an annual crop, it lends itself more readily to genetic innovations than oil crops from trees (Hammond 1995).¹³ Compared with other annual oilseed crops, the soybean’s innate versatility has encouraged the speculative research that is required to extend the filtration

of σ -algebras necessary for product development. Contemporary research efforts continue to work on product reliability issues. Efforts to expand food market opportunities include endeavors to eliminate the off-flavors (Narvel 1997) and to use in a reliable manner highly saturated soybean oil in the production of trans-free margarine (Kok 1998). Instability, for example under oxidation, and other performance inconsistencies remain a major problem in penetrating industrial markets (Hammond 1995) and are a significant area of product development research (e.g., Jiang 2000; Ruger 1999).

Genetics and Information Management

The arguments that will be articulated in this section provide the components of a dynamic framework to explain some of the forces behind the industrialization of animal agriculture. The role of innovation in the industrial evolution of firms over time has been largely neglected in the industrial organization literature. The seminal work explaining Schumpeter's famous thesis on firm evolution in a dynamic framework is attributable to Nelson and Winter (1982). Two of their theoretical findings are relevant to the present study: (a) firms that experiment (innovate) grow relative to firms that imitate, and smaller firms disappear; (b) industries with comparatively high rates of technological progress are characterized by comparatively high levels of average research and development intensity and concentrated structures upon maturity. Both of these conjectures are consistent with events in U.S. poultry and pork production sectors.

As to why agriculture did not industrialize as extensively as other production processes, Allen and Lueck (1998) suggest that the viability of the family farm has much to do with moral hazard problems that arise from the seasonal and random nature of the production environment. In this section, we will point to other consequences of non-uniformities in the production environment that may have affected the structural evolution of agriculture. We claim that non-uniform genetics have comprised a bottleneck in learning about more productive technologies. As such, our argument is similar in flavor to Chandler's thesis that, relative to labor-intensive technologies, capital-intensive production processes tend to require high rates of throughput in order to capture scale economies. Be it at production or processing stages, genetic non-uniformities likely

impede throughput and therefore, consistent with the arguments of Allen and Lueck (1998), may support a more labor-intensive approach to production.

Next, we develop our arguments, first through reference to the recent history of the poultry sector, and then by modeling production efficiencies that arise from uniformities and that are alluded to by commentators on the industry. Finally, we describe changes in the hog sector with reference to the poultry sector.

The U.S. Poultry Sector

As with the reproductive cycle of poultry in comparison with other agricultural livestock, the history of specialized poultry production for meat has been a short and rapidly maturing one. Poultry and egg production had been highly fragmented until the 1920s (Schwartz 1991; Bugos 1992).¹⁴ Indeed, the advent of the commercial broiler industry in the United States is often credited to Mrs. W. Steele, who maintained an egg-laying flock in Maryland during the 1920s. At that time, poultry meat was overwhelmingly the by-product of laying flocks. Egg laying had just begun its journey toward industrialization. Mrs. Steele sold her young laying flock as meat, making a significant profit. Thereafter, she maintained specialized flocks for meat production. Neighbors imitated her actions, thus establishing the Delaware-Maryland-Virginia (Delmarva) Peninsula as the main center of poultry meat production in the United States until after World War II.

Among the main problems facing the young industry were disease control, nutrition, and genetics quality. Chief among the problems arising from poultry DNA were natural tendencies toward seasonal patterns in behavior. The advent of vaccines and vitamin-enriched feed helped move the industry toward realizing greater scale economies through the 1930s, as did innovations in housing infrastructure. And scale economies seemed to go hand in hand with greater vertical coordination.

A key factor in discovering industry cost and revenue potential was the improved control of the bird's genetic profile. The emphasis here was on two general themes, the most obvious being direct productivity enhancement. But, as with feed, vaccine, and housing innovations, flock uniformity was also very important.¹⁵ On the processing side, uniformity facilitated automation, in deboning for example (Schwartz 1991; GAO 1999). At the same time, more value could be added because the raw material would behave

more consistently as steps in processing were introduced. M. J. Thomas, a Kroger supermarket representative, asserted in 1958 that integration in livestock agriculture would help the growing supermarket sector to offer stable volumes of uniform quality to customers.¹⁶ And, as we will argue, greater consistency may have encouraged more experimentation in cost reduction and quality enhancement by removing noise from attempts to learn during production and processing.

Broiler breeding became a commercial business during the 1930s and moved south with the majority of production after World War II. Initially, the emphasis was on purebred lines to ensure flock uniformity. However, by 1950 it was becoming clear that the hybridization techniques developed in the seed corn industry could enhance homogeneity in genetic expression while achieving an additional boost from hybrid vigor. And, for breeding companies, the hybridization approach provided the additional benefit of natural protection for intellectual property because the sold bird could not be used for consistent replication.

By 1960, broiler production was both highly industrialized and integrated; its organizational form did not undergo any substantial changes in the 40 years to follow. Yet, surplus generated by the industry has improved dramatically over those 40 years. Table 1 provides data on U.S. poultry, pork, and beef consumption and prices from 1930 through 2000. It can be seen that the sum of chicken (the term used by U.S. government statistics collectors for spent mature birds) and broiler outputs grew more rapidly over any 10-year period than did either cattle output or hog output. And the relative price of broilers declined dramatically, whether the metric for comparison is cattle prices or hog prices. For example, the price of broilers relative to the hog price declined by about 2.3 percent per year from 1940 through 2000. The decline relative to the beef price was 2.6 percent for the same period.

The rise of poultry consumption was due in part to productivity effects in commodity production, the ability of the industry to differentiate product, and other means of adjusting to consumer demands (Schwartz 1991; Hudspeth 1989). In 1928, broilers were killed at 112 days and at 1.7 kg, with feed conversion efficiency of about 13.3 kg feed per kg weight gain (Bugos 1992). By 1994, 37-day broilers weighed about 1.7 kg, while feed conversion efficiency was about 1.68 kg feed per kg weight gain to 37 days (Nicolson

TABLE 1. Animal production and prices, United States, 1930–2000

	1930	1940	1950	1960	1970	1980	1990	2000
Quantity (mil lbs) ^a								
Chicken	2,643	2,158	2,310	1,142	1,185	1,178	981 ^e	1,112 ^e
Broilers ^d	^b	414	1,944	6,017	10,820	15,538	25,631	41,623
Hogs	15,176	17,043	20,214	19,203	21,861	23,402	21,287	25,730
Cattle and Calves	13,263	15,702	21,185	28,796	39,521	40,284	39,202	42,842
Prices (\$/cwt)								
Chicken ^c	18.40	13.20	22.20	12.20	9.10	11.00	9.60	5.70
Broilers ^c	^b	17.30	27.40	16.90	13.60	27.70	32.60	33.60
Hogs	8.84	5.390	18.00	15.30	22.70	38.00	53.70	42.30
Cattle	7.71	7.56	23.30	22.90	34.50	62.40	74.60	71.30

Source: USDA-NASS *Agricultural Statistics*, various.

^a Liveweight.

^b 97 million pounds of broilers were reported in 1934 at price 19.3¢/lb.

^c Reported as ¢/lb.

^d Not included in farm production of chickens.

^e Reported as pounds sold.

1998). As for product differentiation, it is believed by some observers that poultry meat is about 20 years ahead of other meats in tailoring products to value-added consumer submarkets (Kilman 2001). In the model to follow, we provide an explanation of the origin of this performance differential between poultry and other meats.

Incentives to Learn

Environmental control has always been recognized as a significant factor in determining (static) producer performance (see, e.g., Lacey 1999 or Ritchie 2001). Perhaps more important, however, are the implications of a controlled environment for dynamic performance, and modern poultry farms are well suited for experimentation. In the typical poultry production contract in the United States, the integrator attains considerable control over the production environment by imposing genetic, feed, medication, and housing inputs. In assessing how the role of research in the boiler industry may change in the new century, Nicolson (1998) has stated:

...the gap between the conditions for chickens on research units and the conditions on commercial farms is widening. In most cases, the farms are better equipped to monitor environmental conditions and feed intakes on a frequent basis than the trial units. The commercial farm will be made up of a number of large houses up to 50,000 birds

and, in a more modern unit, be equipped with pan feeders, nipple drinkers and sophisticated ventilation systems which control the temperature as well as the humidity and CO₂ concentration. Daily feed allowances and body weights may be closely monitored by a computer controlled system which allows the stockman hour-by-hour control.

It would seem then that while the industrialization of broiler production may have enabled the sector to avoid transactions costs impediments to glean better technical and economic performance from the livestock, sector structure was important for dynamic process related reasons as well.¹⁷ The process would appear to have been a mechanism for delivering continued improvements in performance. In the model to follow, we will seek to capture one means through which the process might give rise to dynamic productivity effects.¹⁸

Let the aggregate property to be managed, in this case a flock or herd, be composed of n genetic types labeled 1 through n . Fractions $a_i \geq 0$ of the aggregate are of the i th type, $\sum_{i=1}^n a_i = 1$. The curious entrepreneur has assembled a continuum of conjectures that he or she would like to try out on the next lots of the aggregate to enter the production process.

The conjectures can be ranked in terms of their potential according to a unidimensional index of potential, $g(b; \kappa, q, \eta T) > 0$, where each conjecture can be tested independently, that is, without interfering with each other. Variable $b \in [\underline{b}, \bar{b}] \subset \mathbb{R}$ is an index of projects, and q is the level of output at the entrepreneur's firm. The ranking gives $g_b(b; \kappa, q, \eta T) > 0$. Parameter κ is an index of curiosity (about serendipitous events) in assembling these conjectures, and we assume that the more curious operator has collected a stronger portfolio of conjectures so that $g_\kappa(b; \kappa, q, \eta T) > 0$. It is also assumed that the potential increases with q because innovations can be leveraged over larger volumes of output. Variable η is nonnegative and random, reflecting the consequences of uncontrolled aspects of the production environment per unit of time. Variable T is the age at slaughter so that ηT is a measure of cumulative randomness in the general production environment over the duration of the production process. We hold

that $g(b; \kappa, q, \eta T)$ is decreasing in argument ηT so that noise confounds the attainment of insights.

Conjecture b , when implemented in a production process, carries with it profit impact $\varepsilon_{i,b}$ for the i th genetic type. *Ex ante*, the $\varepsilon_{i,b}, i \in \{1, 2, \dots, n\}$ are random but there is no noise in observing the $\varepsilon_{i,b}$ and the *ex post* observed impacts are subsequently stable over time. Upon trying out conjecture b , the entrepreneur believes that his or her business will be subjected to a profit impact of $\bar{a} \cdot \bar{\varepsilon}_b$ if the index of potential is omitted. Here, $\bar{a} \cdot \bar{\varepsilon}_b \equiv \sum_{i=1}^n a_i \varepsilon_{i,b}$ is the type-weighted impact of b on profits, ignoring $g(\cdot)$ and the option not to implement the technique under inquiry. The index enters in a multiplicative manner, so that the one-time profit impact of the innovation is $g(b; \kappa, q, \eta T) \bar{a} \cdot \bar{\varepsilon}_b$. Random variable η is held to be independent of $\bar{\varepsilon}_b$, and a technique will only be introduced if it improves profit, that is, if $\max[\bar{a} \cdot \bar{\varepsilon}_b, 0] \geq 0$. Each experiment requires sunk cost $c > 0$, and the continuous-time discount rate per unit of time over the production period is given by $r > 0$. We hold that the consequences of most experiments will only be identified at slaughter, so that benefits should be discounted by the factor e^{-rT} .

The profit-driven operator will be willing to check out a conjecture if and only if the capitalized, discounted, expected benefit exceeds cost; $Y(b; a, \kappa, q, c, T) \geq 0$ where

$$Y(b; a, \kappa, q, c, T) = \frac{E\{g(b; \kappa, q, \eta T)\} E\{\max[\bar{a} \cdot \bar{\varepsilon}_b, 0]\}}{r e^{rT}} - c, \quad (6)$$

and $E\{\cdot\}$ signifies the expectation operator over the pertinent random vector. Here a is an index of homogeneity as reflected by the composition of vector \bar{a} . The precise nature of the index will be explained shortly. Denote the “break-even” project satisfying $Y(b; \cdot) = 0$ as $b^*(\cdot)$ which is implicitly a function of the other arguments of $Y(\cdot)$ in (6). If the weighting measure on $[\underline{b}, \bar{b}]$ is $\phi(A)$ for $A \subseteq [\underline{b}, \bar{b}]$, then the measure of implemented projects is $\phi([b^*, \bar{b}])$. A comment is warranted concerning the appropriateness of objective function (6). The function assumes that the firm cannot be an easy-rider on

innovations by other firms. In reality, easy-riding behavior will likely dampen incentives to innovate.

At this juncture, explicit structure is required on the $\bar{\epsilon}_b$ if we are to make sense of when standardizing innovations have determinate effects on the set of conjectures that solve $Y(\cdot) \geq 0$. First, while realization $\bar{\epsilon}_b$ depends upon conjecture b , the underlying distribution from which it is drawn is held to be common across all conjectures. Second, we assume that the components of $\bar{\epsilon}_b$ are exchangeable.¹⁹ For exchangeable random variables, it is well known among mathematical statisticians that function $E\{\max[\bar{a} \cdot \bar{\epsilon}_b, 0]\}$ is symmetric and convex in \bar{a} (see, e.g., Marshall and Olkin 1979, pp. 287–88). Therefore, the function is Schur-convex. This means that $E\{\max[\bar{a} \cdot \bar{\epsilon}_b, 0]\}$ is larger under \bar{a}'' than under \bar{a}' whenever \bar{a}'' majorizes \bar{a}' .

DEFINITION 3. (See Marshall and Olkin 1979, p. 7.) For vectors $\bar{u} \in \mathbb{R}^n$ and $\bar{v} \in \mathbb{R}^n$, denote the respective k th largest components as $u_{[k]}$ and $v_{[k]}$. Write $\bar{u} \prec \bar{v}$ if

- a. $\sum_{k=1}^i u_{[k]} \leq \sum_{k=1}^i v_{[k]} \forall k \in \{1, 2, \dots, n-1\}$; and
- b. $\sum_{k=1}^n u_{[k]} = \sum_{k=1}^n v_{[k]}$. Then vector \bar{v} is said to majorize vector \bar{u} .

To illustrate, $(\frac{1}{8}, \frac{3}{8}, \frac{1}{2}) \prec (0, \frac{1}{3}, \frac{2}{3})$ because $\frac{1}{2} \leq \frac{2}{3}$, $\frac{7}{8} \leq 1$, and $1 = 1$. We will have particular interest in the extremes of the majorization relation;

$$(n^{-1}, \dots, n^{-1}) \prec (a_1, \dots, a_n) \prec (1, 0, \dots, 0) \tag{7}$$

for any \bar{a} with nonnegative components and on-the-unit simplex, that is, $\bar{a} \cdot \bar{1} \equiv 1$.

We are now in a position to analyze determinants of incentives to experiment.

DEFINITION 4. The aggregate as represented by \bar{a}'' is said to be more homogeneous than the aggregate as represented by \bar{a}' if $\bar{a}' \prec \bar{a}''$.

While relation \prec is a partial ordering, our concern is only with instances where vectors can be ordered. For convenience, then, we define the index of homogeneity a with some monotone map $\vec{a}' \rightarrow a' \in \mathbb{R}$ under which $\vec{a}' \prec \vec{a}'' \Leftrightarrow a' < a''$.

PROPOSITION 4.

- a. An increase in the homogeneity index, the curiosity index, or the level of firm output increases the number of experiments engaged in.*
- b. An autonomous reduction in the slaughter date also increases the rate of experimentation.*

Noise, be it through genetics or other factors, reduces the expected returns to tinkering. In the extreme, let $\vec{a}'' = (1, 0, \dots, 0)$, which could be interpreted as a cloned aggregate. This would elicit the largest level of experimentation. A clarification concerning the proposition involves the choice of the verb “tinker.” It was chosen to emphasize the engineering, rather than scientific, origin of the innovations that we seek to model. The realities of running a competitive business may leave little room for the paradigm-shifting innovations that occasionally may arise from fundamental research.

The economics underpinning part (a) bears comparison with the concept of an economic tournament, a common remunerations structure in poultry production (Knoeber 1989). Economic tournaments, if thoughtfully constructed, shift the shared performance risks of participants onto the contractor who may be best able to bear them. By removing this noise, performance incentives can be sharpened. Likewise, the removal of background noise allows for the sharpening of incentives to experiment.

We have supposed that the set of conjectures was fixed and invariant to T . If, instead, the density of conjectures with index b rises in strict proportion to T , then b^* can be interpreted as the threshold hypothesis that would be accepted at any moment as hypotheses are recorded for possible testing. Note that the value of index a likely also will affect the flow of conjectures. Ideas are likely to arise more readily if the level of background noise is low, so a large value of a will likely also improve the flow and quality of conjectures. A low value of T , too, likely will have this effect. This is because

the entrepreneur will be more certain that events other than those known to him or her did not affect the outcome of events.

Proposition 4 provides an explanation as to why the characteristics of poultry production assumed an industrial nature earlier than did those of later-maturing livestock. As T declines, the rate of experimentation picks up. An assembly-line approach is possible only when the production characteristics are sufficiently well understood and controlled. Thus, there should be a negative correlation between age at slaughter and the “industrialization” status of production practices.

To establish interactions between the curiosity index and the impact of environmental homogeneity on experimentation, we invoke a strict, increasing (decreasing) single-crossing condition on $Y(\cdot)$. The condition is that $d[Y_a(\cdot)/Y_b(\cdot)|_{Y=0}]/d\kappa > (<) 0$ for all argument evaluations, so that the indifference curves cross just once as κ changes.

PROPOSITION 5. *Assume that b is uniformly distributed on $[\underline{b}, \bar{b}]$.*

- a. Let the strict, increasing (decreasing) single-crossing condition hold. Then an increase in homogeneity, $a' \rightarrow a''$, leads to a larger (smaller) increase in experiments done by the more curious than by the less curious.*
- b. An increase in homogeneity, $a' \rightarrow a''$, leads to a larger (smaller) increase in experiments done at high c than at low c if $-d^2 \ln[g(\cdot)]/db^2 > (<) 0$.*

Similarly, a strict single-crossing condition on $Y(\cdot)$ as q changes would generate a result for output analogous to that for the curiosity index. Notice that the uniformity of b across $[\underline{b}, \bar{b}]$ is important in Proposition 5. Were b not uniform, then other explicit conditions on the distribution of b would be required to map the impact on threshold conjectures into the impact on experiments conducted.

Hog Sector

Hogs for meat in the United States are slaughtered at 5 to 6 months of age, while beef cattle are seldom slaughtered below 15 months of age. Similarly, reproductive cycles are roughly twice as long for cattle relative to hogs. Proposition 4 suggests that hogs, if at

all, should undergo industrialization after poultry but before cattle. This theory is broadly supported by the evidence (Ritchie 2001). Beef production at the later stages is now overwhelmingly (85 to 90 percent) conducted in large feedlots in the High Plains region, but the efficiencies gained are largely scale in nature and the coordination of the production process from conception to consumption is very limited.

The U.S. hog industry is further down the industrialization trail and has undergone significant structural realignment since the late 1980s. Consolidation in the pork industry is occurring at a rapid pace. In 1988, 32 percent of hogs marketed came from operations producing less than 1,000 head per year, and 7 percent came from operations over 50,000 head.²⁰ By 1997, only 5 percent came from 80,000 operations marketing less than 1,000 head per year and 37 percent came from 145 operations marketing over 50,000 head each. In 1994, the top five producers owned about 8 percent of the swine breeding herd (sows) and the top 25 producers owned 15 percent. By 1999, the top producer owned 12 percent, the top 5 owned 19 percent, and the top 25 owned 34 percent of the breeding herd. Further, much of the integration that is occurring is vertical. By 2002, the meat packer Smithfield, with 744,000 sows or 12.4 percent of the sow herd, was the leading producer. Meat packers Seaboard and Cargill also were counted among the top five.

Important gains in efficiency have been achieved through genetics content and artificial insemination. The number of pigs per litter has increased 12.3 percent from 7.86 in 1989 to 8.83 in 2002. The number of litters per sow also has increased, and the number of pounds of pork produced per sow in the breeding herd has grown by 27 percent between 1989 and 1999. Similar to poultry, significant increases in feed efficiency have been realized.²¹

From our observations, it is evident that structural changes are underway in the pork industry that parallel those in the broiler industry. These changes have been facilitated by increased genetic standardization, which helps to create an environment conducive to experimenting.²² New production technologies, biased toward larger, more coordinated production processes, also have facilitated these structural changes. For example, electronic technologies, which monitor water and feed intake in hog facilities, can provide advanced warning of impending disease outbreaks and needed remedial responses. Such monitoring activities also complement experimentation by removing

stress-related noise from the production environment. Other production technologies, including artificial insemination, segregated early weaning, all-in/all-out turns, split sex, and phase feeding, promote herd uniformity and thus are likely to enhance the learning environment.

As reported in Onishi et al. (2000), clones of mature pigs were farrowed in July 2000. Mature sheep, cattle, and goats had been cloned over the preceding three years. In April 2002, clones from slaughtered beef cows were calved, allowing *ex post* selection on graded meat characteristics. Motivating the Onishi et al. study were the potential for clonal propagation of phenotypes in pork meat production and the possibility of xenotransplantation of organs into humans.²³ The field has progressed so rapidly that cloned livestock were on farms by June 2001. In that month, the U.S. Food and Drug Administration informed two clone propagators that regulator consent would be required before products from clones could enter food and feed markets (Regalado 2001). Why this demand for cloned livestock in commercial production exists is not as obvious. Our theory suggests that breakthroughs in precision breeding may have as much effect on the rate of productivity growth through improved production practices and increased opportunities for informative tinkering as they do directly through improving herd genetic endowments. Microeconomic data from the poultry industry may be the best source for insight into the origins of productivity improvements and what may be in store for other livestock production sectors.

Conclusion

The implications of recent advances in life and information sciences are likely to be as dramatic for agriculture as for other economic sectors. The intent of this paper has been to identify pathways through which innovations in obtaining and using biological information could affect agriculture. We have shown how a refinement of the information sets available to processors can translate into a wider array of offered food products. And we have suggested a dynamic pathway through which information that allows uniformity in the production environment can enhance productivity.

We do not claim that these are the only pathways through which biological information contributes to improved food sector productivity because a consequence may

have many contributing factors. We do conjecture that these are some of the most important pathways. But the general topic of how information affects the amount and variety of food offerings has not yet received the attention it deserves. Given the present rate of technical progress in the life and information sciences, and given the growing debate over policies to guide the industrialization of agriculture, it is crucial that a thorough analysis of the implications of these innovations for the nature of food production be undertaken.

Endnotes

1. Knoeber (1989), in rationalizing the use of long-term broiler production contracts possessed of stipulations that establish bonding, has articulated essentially the same point. The informativeness of technology trials on the part of poultry contractors will vary directly with the stability of the grower base.
2. This discourse on martingales relies heavily on Durrett 1996, pp. 231-33. Allen (1983), among others, has modeled economic information in this manner.
3. See Durrett 1996, p. 1, on the definition of a σ -algebra. For the set of possible outcomes, Ω , the σ -algebra is a collection of subsets such that (a) if $A \in \mathcal{F}_i$ then the complement of A in Ω , i.e., Ω/A , is in \mathcal{F}_i , and (b) if $\{A_j\}_{j=1}^{n \leq \infty}$ is a possibly countably infinite sequence of sets in \mathcal{F}_i , then $\cup_{j=1}^{n \leq \infty} A_j$ is also in \mathcal{F}_i .
4. Caution is warranted because, for quite technical reasons, the analogy cannot be taken literally as $i \rightarrow \infty$. See Dubra and Enchenique 2001 for a careful treatment of filtrations as a means of modeling information.
5. For those not familiar with using martingales, or the rational expectations models that often apply them, it is useful to bear in mind that the smallest (i.e., coarsest) information set always wins out when taking the expectation of linear functions, i.e., $E[\omega_\infty(K) | \mathcal{F}_i(K)] = \omega_i(K) = E[E[\omega_\infty(K) | \mathcal{F}_{i+1}(K)] | \mathcal{F}_i(K)] = E[E[\omega_\infty(K) | \mathcal{F}_i(K)] | \mathcal{F}_{i+1}(K)] \forall i \in \{0, 1, \dots\}, \forall K \in \mathbb{R}_+$.
6. Since $\omega_i(K) \in [0, 1]$, the process is uniformly integrable (Durrett 1996, p. 259). If $\omega_i(K)$ is a martingale, then it is known that $\lim_{i \rightarrow \infty} \omega_i(K) \in [0, 1]$ converges almost surely and in L^1 space, i.e., $\lim_{i \rightarrow \infty} \int |\omega_i(K) - \omega_\infty(K)| dH_i[\omega_i(K)] < \infty$ (Durrett 1996, p. 261). And so, for a filtration of infinite sequence length, we may take for granted the existence of a limiting random variable.
7. Although costly, beef farmers occasionally sonoscope feeder calves for muscling characteristics and use the information to form homogeneous feedlot pens. Referring to attempts by beef packers to replicate the success of poultry processors in meat market penetration, Kilman (January 2001) wrote:

Still, one of the biggest complaints consumers have about red meat is its lack of consistent quality. So, to achieve better uniformity without trying to control the entire process, Tyson plans to accelerate IBP's strategy of doing more prepara-

tion work on beef and pork. Marinating, pre-cooking and hand-trimming can eliminate a lot of the variety that comes with slaughtering scores of cattle breeds, all of which are different shapes and sizes....

Tyson, a poultry processor, was then in the process of purchasing IBP, a beef and hog packing company. Also, Amana Beef Products of Amana, IA, has engaged in hand selection off the production line for its line of premium cuts.

8. See Theorem 2.3, p. 232, in Durrett 1996.
9. Assumption 3 could be relaxed without compromising the insights we will develop. But, because this route would require additional notation, we choose not to introduce sorting costs.
10. The notation $\inf\{S\}$ represents the infimum, or greatest lower bound, of set S . The notation $\sup\{S\}$ represents the supremum, or least upper bound, of set S .
11. See the Appendix for formal proofs of propositions not demonstrated in the text.
12. A related issue has been studied in Athey and Levin 2001, where the context is a signal-contingent investment by a risk-averse firm.
13. Annual crops are also better suited to indoor and accelerated global research programs.
14. Most of the materials in this section report facts and opinions in Roberts 2000, Schwartz 1991, and Bugos 1992.
15. These two themes may be linked. Rapid productivity improvements in a few traits are often achieved at the expense of other traits. Productive animals may be sicklier, and sickly creatures need more attentive husbandry unless the herd is relatively uniform. Herd homogeneity allows for the realization of scale economies in catering for the failings of fragile herd members. The skeleton and heart of a rapidly muscling broiler have difficulty supporting the maturing bird. Lameness and heart failure are serious problems in modern broiler production.
16. The role of vertical links on food sector structural dynamics is likely to have been much more involved. See Bonaccorsi and Guiri 2001 for an interesting empirical study of vertical networks and dynamics in aviation sector markets.

17. Concerning a static environment, control is a precursor for the capacity to optimize over the control variable. Housing often provides the opportunity to control. Dahl (2001) reviews the literature on manipulating light exposure to optimize commercial bovine milk production.
18. In a less formal framework, and concerning product design projects, Thomke (2001) provides interesting discussions on process engineering to take advantage of technological innovations that reduce the costs of experimentation.
19. Consider the distribution function $F(x_1, x_2, \dots, x_n)$ for some vector x . The random variables are exchangeable if the value of $F(x_1, x_2, \dots, x_n)$ is invariant to permutations of coordinate values. For example, this is true of multivariate normal random variables if the marginals are common and the common correlation parameter is nonnegative.
20. The estimates are based on *Successful Farming Online*; Lawrence, Grimes, and Hayenga 1998; and USDA-NASS *Hogs and Pigs*, various online.
21. Based on the Iowa Swine Enterprise Records Program participants, feed efficiency has gone from 4.1 lb feed to 1 lb gain in 1979 to 3.8 lb in 1989 to 3.5 lb in 1999 for farrow-to-finish operations.
22. By 2001, just 10 companies accounted for the majority of genetic seedstock marketed by swine companies (Ritchie 2001).
23. The second author of that study, M. Iwamoto, was employed at the time of publication by a meat packing company.

Appendix

Proof of Proposition 3

Fix the value of K , and consider $V[\mathcal{F}_0(K)]$ so that only product A is produced (see Assumption 1). Now, from Proposition 1, $V[\mathcal{F}_i(K)]$ is monotone in $\{i\}$ for any value of K . Define $G^*[\{i\}] = \max_K V[\mathcal{F}_i(K)] - K$. If $G^*[\{i\}] > G^*[\{0\}]$ then both A and B must be produced under $\{i\}$, for otherwise $G^*[\{i\}] = G^*[\{0\}]$. It cannot be that only B is produced under information set $\{i\}$ because that would necessarily involve a violation of the martingale property, i.e., $\{\omega_i(K) : \omega_i(K) \geq \delta/L\}$ has null probability for some $K \in \mathbb{R}_+$ and yet $\omega_0(K) = E[\omega_i(K)] \geq \delta/L$ where $\omega_i(K)$ is bounded.

Because Proposition 1 asserts that $G^*[\{i+1\}] \geq G^*[\{i\}]$, if $G^*[\{i\}] > G^*[\{0\}]$ then both A and B must be produced under $\{i+1\}$ too. If $G^*[\{i\}] = G^*[\{0\}]$, then Proposition 1 asserts that $G^*[\{i\}] = G^*[\{i-j\}] \forall j \in \{0, 1, \dots, i\}$ and only A is produced for $j \in \{0, 1, \dots, i\}$. All this leads to the conclusion that there exists some threshold $\{i\} = \{i\}^*$ such that (a) and (b) apply. \square

Proof of Proposition 4

For part (a), we will demonstrate the result concerning index a . The other effects can be shown similarly. From the definition, together with the Schur-convexity of function $E\{\max[\bar{a} \cdot \bar{\epsilon}_b, 0]\}$, we have that $a' < a'' \Rightarrow E\{\max[\bar{a}' \cdot \bar{\epsilon}_b, 0]\} \leq E\{\max[\bar{a}'' \cdot \bar{\epsilon}_b, 0]\}$. Fix parameters other than a and b . Remembering that the distribution from which $\bar{\epsilon}_b$ is drawn is not dependent upon b , we see from $g_b(b; \kappa, q, \eta T) > 0$ that the b satisfying $Y(\cdot) = 0$ is decreasing as $a' \rightarrow a''$.

For part (b), observe that the denominator in equation (6) increases as T increases. Concerning the numerator, we have $dE\{g(\cdot)\}/dT = E\{\eta dg(\cdot)/d(\eta T)\} \leq 0$. Given

$g_b(\cdot) > 0$, it follows that $db^*/dT > 0$, and the measure of experiments engaged in declines with the age at slaughter because set $[b^*, \bar{b}]$ contracts. \square

Proof of Proposition 5

Relation $d[Y_a(\cdot)/Y_b(\cdot)|_{Y=0}]/d\kappa > 0$ implies that $db/da|_{Y=0}$ is decreasing in the value of κ , i.e., $b^*(a'', \kappa^1) - b^*(a', \kappa^1) < b^*(a'', \kappa^0) - b^*(a', \kappa^0) \forall \kappa^0 < \kappa^1$. Interpreting, the threshold for engaged-in experiments decreases by more for the very curious than for the less curious. Relation $d[Y_a(\cdot)/Y_b(\cdot)|_{Y=0}]/d\kappa < 0$ implies the reverse.

As to part (b), write $r(b) = E\{g(b; \kappa, q, \eta T)\}$ and $s(a) = E\{\max[\bar{a} \cdot \bar{\epsilon}_b, 0]\}$. Note that if c increases then b^* increases to restore equality in (6). So $d[Y_a(\cdot)/Y_b(\cdot)|_{Y=0}]/dc$ has the sign of $d[Y_a(\cdot)/Y_b(\cdot)|_{Y=0}]/db$. This in turn has the sign of $[r_b(b)]^2 - r(b)r_{bb}(b)$, i.e., of $-d^2 \ln[g(\cdot)]/db^2$. Therefore, $b^*(a'', c^1) - b^*(a', c^1) < b^*(a'', c^0) - b^*(a', c^0) \forall c^0 < c^1$ if $d^2 \ln[g(\cdot)]/db^2 < 0$. And $d^2 \ln[g(\cdot)]/db^2 > 0$ reverses the inequality on the differences in project threshold values. \square

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