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 profits, the incentive to upgrade quality, and the incentive to engage in product differentiation activities. We also show how information on agricultural raw materials can improve processing efficiencies and the opportunities for attaining any given point in product attribute space. A theory on how genetic uniformity can enhance the rate of process experimentation, and so the rate of technical change, is also developed.

JEL classification: D2, O3, L0, N5

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Two of the most important economic innovations over the past half century have been the ability to store and process large volumes of data and the expanding array of techniques that increasingly enable the modification of life forms to specific ends. In agriculture, the latter has been a significant factor in the Green Revolution, the advent of genetically engineered crops, and the impressive productivity growth rates that have been achieved by commercial poultry and hog growers.

Perhaps not surprisingly, the effects of innovations in data management have not been nearly as pervasive in agriculture. To be sure, many large farms do use personal computers. And such bulk inputs as fertilizer, feed, and seed are likely cheaper because of the use of modern information technologies in manufacture and distribution. Also, precision farming techniques have become popular in some parts of the world since the middle 1990’s (Khanna). But these applications of information management techniques would not appear to have had as far-reaching effects as have changes in genetic inputs.

Notwithstanding, there is a growing need for managing information about production activities. During the 1990s, and through 2001, evidence has emerged that consumer and processor demands for information about on-farm activities that affect quality attributes have not been met. For the purpose of motivating the category of issues to be addressed in this paper, we will classify instances of demand for information on production activities into ‘non-genetic’ and ‘genetic’. As will become apparent in the discussion to follow, the boundary between these categories is not sharp. In addition to the genetic dimension, we also introduce a ‘demand origin’ dimension to the classification, where the demand may come from the production level itself, from processors, or from consumers.

Table 1 provides the classification matrix, together with some sample entries. Our concern is not with the lower three boxes (N1 through N3), or even directly with the consumer (G3 and N3), so we will do no more than justify our sample entries in these boxes. Consumers may be concerned about such ethical issues as animal welfare during production, and about health risks. In seeking to satisfy the consumer, the processor will also have regard for these issues. In addition, the processor will desire information pertaining to the processability of the raw materials...
it receives. The grower may demand information on inputs in order to protect against disease related productivity disruptions, where a disruption may arise directly from the disease or indirectly through public measures to control the disease.

It is clear that many consumers would rather not consume genetically modified products (Howie), and so we have placed genetic modification status in boxes G2 and G3. In addition, there exist niche markets for breeds associated with particular traits, e.g., Wagyu beef or Jersey milk. As a consequence, the processor too will have an interest in grower-level information on genetic inputs. In addition, the processor will have an obvious interest in the (mean) quality of the genetic lines it will have to work with.

Our interest in this paper is in the remaining entries in boxes G1 and G2. The goal of the paper is to identify and analyze mechanisms through which genetics and information interact in the endeavor of meeting consumer demands. Section 2 will focus on processor interests in information on product reliability when engaging in activities to add value to raw materials coming from growers. Demographic trends and rising incomes have created demands for niche products that provide the consumer with uniform experiences (Barkema, Drabenstott, and Welch). In many cases, processors must add further value to meet the demands of restaurants and domestic consumers. Processors will only attempt to differentiate their product if they know that the raw material will perform reliably during processing. In our first model, we will characterize how information may play a role in the decision to develop new markets for product derivatives. As technical attributes of the raw material become more certain, more product differentiation will occur. We illustrate the model with reference to the soybean crop through the 20th Century.

In Section 3 we show that resolving uncertainty may be only part of the story in determining the level of product differentiation. The transactions costs of sorting may also be important. If the available technologies admit an expansion of opportunities when product of known attributes are sorted, then, absent non-convexities, information on the attributes converts to an expanded offering of processed products and lower cost products. Sorting technologies can take two forms. Ex-post sorting occurs when it is possible to categorize realized product according to certain
economically relevant traits, and this information is then used to re-arrange the product into category-conditioned homogeneous lots. Ex-ante sorting occurs if available information allows one to believe that production from a given source is homogeneous so that it does not need to be sorted ex-post. The transactions costs, including information acquisition and product degradation costs, associated with ex-post sorting may be prohibitive.

To provide a sense of what we mean here, we note that many of the main processes in food manufacture involve separation and concentration activities. Even if one knows exactly the composition of raw materials, these processes are costly in terms of energy, capital use, and quality degradation. Input and information acquisition costs aside, product degradation may ensure that it may not be worthwhile to purify (i.e., sort ex-post) heterogeneous raw materials. Genetic technologies that allow ex-ante sorting enable the processor to circumvent the prohibitive transactions costs. We will provide a set theoretic framework in which to think about such issues.

Section 4, in overviewing the recent history of poultry production, identifies some information management efficiencies that can arise from information on the nature of raw materials. The section develops two arguments concerning the benefits of control. The first shows that if the processing technology is Leontief in nature and weak links limit the rate of throughput then processing plant efficiencies can be improved by ex-post sorting of raw materials into relatively homogeneous batches before subjecting the materials to processing.

The second argument is that ex-ante sorting in the form of homogeneous raw materials render experiments in production (and processing for that matter) more informative because controlled experiments provide less noisy results for interpretation. As a result, more experiments are engaged in at the production and processing stages. We provide evidence to show that this learning story is consistent with events in U.S. poultry and hog sectors over the past 70 years. Knoeber, 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.
This framework, together with the earlier models of the static role of information on valued added, also lend support to the notion that the keys to an agricultural sector that delivers cheap, differentiated products are a strong knowledge base concerning genetics, the capacity to cheaply sort production into homogeneous lots, and an highly controlled production/processing environment. On the latter, a low age to 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. Finally, we suggest that cloning technologies, in advancing the capacity to homogenize raw materials, may have a profound impact on commercial animal agriculture. The study concludes with a brief summary.

**Information and Value Adding Activities**

An agricultural processor is in the business of buying a raw commodity, be it animal, vegetable, or grain, and applying other inputs to transform the raw material into some product. The processor faces the dilemma of choosing between using raw input to process a standard product or using it to process a value added product. The standard product, A, generates unit revenue \( P \) for sure because the technology 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 where human intelligence can better accommodate variation.

The alternative product, B, generates unit revenue, *net* of additional costs, amounting to \( P + \delta \) if all goes as planned. However, perhaps because the genetic materials are inconsistent or the technology is insufficiently well understood, there is a risk that the product does not turn out as planned and a loss is incurred. We identify the state-contingent loss as \( L \) and capture the risk by the *true* loss probability \( \omega_{\omega}(K) \), 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 \( K \in \mathbb{R}_+ \).

The loss probability is itself a random variable, and depends on a multiplicity of factors such
as genetic attributes. In an environment where the processor is fully informed about the determinants of $\omega_\ast(K)$, where these determinants can be observed and where sorting incurs no costs, product will be sorted into that which is processed and that which is not. For a given $K$, the otherwise unconditional distribution of product reliability is $H^\ast[\omega_\ast(K)]$. This might be considered to represent the ex-ante stock of information about raw material that the processor might learn upon inspection. Assuming risk neutrality, or assuming large numbers of units of raw materials and appealing to the Glivenko-Cantelli theorem (Durrett, p. 59), expected product revenue reflects the processor’s benefit function. Under the standard product the expected benefit is $P$. Under the alternative product the expected benefit is $P + \delta - L \omega_\ast(K)$ so that $\omega_\ast(K) = \delta/L$ is the cut-off point such that a unit with $\omega_\ast(K) < (>) \delta/L$ should (should not) be subjected to value adding processes. The cut-off point is independent of the value of $K$, although the fraction of raw material that is processed is not.

The added value, relative to the base of not subjecting any product to the value adding activity, of sorting the product to the fully informed processor is

\[ V(K) = \int \text{Max}[0, \delta - L \omega_\ast(K)] dH^\ast[\omega_\ast(K)], \]

where fraction $H^\ast[\delta/L]$ is processed and fraction $1 - H^\ast[\delta/L]$ 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. Commence with the baseline empty information set, $\mathcal{F}_0(K) = \emptyset \ \forall \ K \in \mathbb{R}_+$, that 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 distribution function $H^0[\omega_0(K)]$.

1. This discourse on martingales relies heavily on Durrett, pp. 231-233. Allen, among others, has modeled economic information in this manner.
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 $\omega_1(K)$. And continuing, we may conceive of a, possibly infinite, sequence of increasingly informed environments $\{\mathcal{F}_i(K)\}_{i=0}^{\infty}$ where $\mathcal{F}_0(K) \subset \mathcal{F}_1(K) \subset \cdots \subset \mathcal{F}_i(K) \subset \cdots \subset \mathcal{F}_n(K)$ and each is a $\sigma$-algebra.² Such a collection of information sets is called a filtration. One might think of the filtration as a set of documents that might accompany raw materials where document $\mathcal{F}_0(K)$ reveals no information about the material, document $\mathcal{F}_1(K)$ reveals one relevant piece of information and, generally, document $\mathcal{F}_i(K), i \in \{1, 2, \ldots \}$ reveals one additional relevant piece of information over that contained in $\mathcal{F}_{i-1}(K)$.³

We can associate with the filtration a sequence of random variables $\{\omega_i(K)\}_{i=0}^{\infty}$. For each $K$, the largest information set, $\mathcal{F}_n(K)$, contains all relevant information. To avoid the possibility of confusion at a later juncture, we will 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, i.e., of $\omega_\infty(K)$.

Expectations with respect to $H_0^0[\omega_0(K)]$ are denoted by $E[\cdot \mid \mathcal{F}_0(K)]$. We make

Assumption 1. $\omega_0(K) = E[\omega_\infty(K) \mid \mathcal{F}_0(K)] \geq \delta / L \ \forall K \in \mathbb{R}_+.$

Viewing (1), this assumption states that, irrespective of the level of investment, it is rational not to attempt to add value to any product 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

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² See Durrett, p. 1, on the definition of a $\sigma$-algebra. For the set of possible outcomes, $\Omega$, the $\sigma$-algebra $\mathcal{F}_i$ is a collection of sub-sets such that a) if $A \in \mathcal{F}_j$ then the complement of $A$ in $\Omega$, i.e., $\Omega \setminus A$, is in $\mathcal{F}_j$, and b) if $\{A_j\}_{j=1}^{\infty}$ is a, possibly countably infinite, sequence of sets in $\mathcal{F}_j$, then $\bigcup_{j=1}^{\infty} A_j$ is also in $\mathcal{F}_j$.

³ Caution is warranted because, for quite technical reasons, the analogy cannot be taken literally. See Dubra and Enchenique for a careful treatment of filtrations as a means of modeling information.
4. For those not familiar with using martingales, or 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.,

\[ E[\omega_j(K) | \mathcal{F}_j(K)] = E[\omega_j(K) | \mathcal{F}_i(K)] = E[\omega_{i+1}(K) | \mathcal{F}_i(K)] = \omega_i(K) \]

\[ \forall i, \forall K \in \mathbb{R}_+, \forall j \geq i, \]

then the process of \( K \)-conditioned random variables represented by \( \omega_i(K) \) is said to be a martingale with respect to the filtration.\(^4\) If \( E[\omega_{i+1}(K) | \mathcal{F}_i(K)] \geq \omega_j(K) \forall i, \forall K \in \mathbb{R}_+ \), then the process is said to be a submartingale.\(^5\) Henceforth we will also suppose

**Assumption 2.** For a given level of investment, \( K \), random variables \( \{\omega_i(K)\}_{i=0}^{t=\infty} \) follow a martingale process in the manner of (2) above.

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 and 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, i.e., to known variability. In an environment where there is known variability, it is possible, at least conceptually, to ex-post sort the raw materials.\(^6\)

Each \( \omega_i(K) \) has associated with it an absolutely continuous measure, \( H^i[\omega_i(K)] \), where we

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5. Since \( \omega_i(K) \in [0, 1] \), the process is uniformly integrable (Durrett, p. 259). If \( \omega_i(K) \) is a martingale, then it is known that \( \lim_{i \to \infty} \omega_i(K) \in [0, 1] \) converges almost surely and in \( L^1 \) space, i.e., \( \lim_{i \to \infty} \int |\omega_i(K) | dH^i[\omega_i(K)] < \infty \) (Durrett, p. 261). And so, for a filtration of infinite sequence length, we may take for granted the existence of a limiting random variable.

6. Although costly in the late 1990's, beef farmers occasionally sonoscoped feeder calves for muscling characteristics, and used the information to form homogeneous feedlot pens.
clarify our concept of information as an extension of a $\sigma$-algebra.\(^7\)

**Definition 1.** Make Assumption 2 above. Distribution $H^i[\omega_i(K)]$ is said to be more informative than $H^j[\omega_j(K)]$ whenever $i \geq j$.

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

$$
V[\mathcal{F}_i(K)] = E\left[\text{Max}[0, \delta - L E[\omega_{\omega}(K)] | \mathcal{F}_i(K)] | \mathcal{F}_0(K)\right].
$$

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 the value added activity; and so to access some surplus relative to the ‘plain vanilla’ product.

Now, by the convexity of the Max[$\cdot$, $\cdot$] statement, Jensen’s inequality, and the observation that $E\left[\text{Max}[0, \delta - L E[\omega_{\omega}(K)] | \mathcal{F}_i(K)] | \mathcal{F}_0(K)\right] = E\left[E\left[\text{Max}[0, \delta - L E[\omega_{\omega}(K)] | \mathcal{F}_i(K)] | \mathcal{F}_0(K)\right] | \mathcal{F}_i(K)\right]$, we have\(^8\)

$$
V[\mathcal{F}_n(K)] \geq \ldots \geq V[\mathcal{F}_i(K)] \ldots \geq V[\mathcal{F}_1(K)] \geq V[\mathcal{F}_0(K)].
$$

To interpret the inequalities, we make\(^9\)

**Assumption 3.** Sorting is costless.

Consider now the situation where none of the ex-ante stock of information becomes available

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7. Other economic concepts of information order exist (Chambers and Quiggin, 2001; Athey and Levin, 2000). In particular, Athey and Levin provide an exact notion for ‘more information’ that pertains to our context. We choose not to use it here because the stochastic attributes of such stochastic structures are not nearly as well-explored as the martingale concept by which we will characterize ‘more information’.

8. This is, in part, an application of Bayes’ theorem. See Theorem 2.3 in Durrett.

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 expand the model context in this manner.
to the processor. So \( \{0\} \) is the pertinent information set, and we may write

\[
V[\mathcal{T}_0(K)] = E\left[\text{Max}[0, \delta - LE[\omega_i(K) | \mathcal{T}_0(K)]] | \mathcal{T}_0(K)\right]
\]

(5)

\[
= \text{Max}[0, \delta - LE[\omega_i(K) | \mathcal{T}_0(K)]] = 0,
\]

where the last equality is due to Assumption 1. And so no value adding 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 produce into that which will be processed further and that which will not. It is the action of sorting that underpins relation (4), which may be encapsulated as

**Proposition 1.** The value of a given level of investment increases as the processor becomes more informed.

The above result does not, however, provide insight into the incentive to increase the level of investment. In fact, it cannot do so because the problem is possessed of insufficient structure. We will now place sufficient structure on the problem. Notice that the \( \text{Max}[\cdot, \cdot] \) statement in (3) is decreasing and convex in the random variable. And so the marginal product of investment \( K \) on the part of the processor, and for a given information set \( \mathcal{T}(K) \), is positive if an increase in \( K \) induces a second-degree stochastically dominated shift in \( H[\omega_i(K)] \). For the same stock of raw materials, if an increase in \( K \) induces such a stochastic shift then \( \omega_i(K) \) 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 first ordinate in \( \{i\}, K \) while stochastic dominance orders it by the second 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 due to Topkis.

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

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

**Result 1.** (Topkis) For any sets $S \subset \mathbb{R}$ and $S' \subset \mathbb{R}$, define the partial ordering $S \preceq S'$ as the relation whereby $\inf \{S\} \leq \inf \{S'\}$ and $\sup \{S\} \leq \sup \{S'\}$. If $G(t,K): T \times \mathbb{R} \to \mathbb{R}$ has increasing differences in $(t,K)$ then $\arg\max_K G(t,K) \preceq \arg\max_K G(t,K') \forall t \preceq t'$.

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 $G[\mathcal{F}(K)] = V[\mathcal{F}(K)] - K$ as the processor’s objective to be maximized, Result 1 implies\textsuperscript{10,11}

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

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

a) all larger sets in the filtration will be associated with the production of both $A$ and $B$.

\textsuperscript{10} See the Appendix for formal proofs of Proposition 3 and other propositions not demonstrated in the text.

\textsuperscript{11} Proposition 2 is consistent with Chandler’s 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.
b) *all smaller sets in the filtration will be associated with the production of just A.*

Notice that Proposition 3 does not assume increasing differences. But, taken together, i.e., under the assumptions in Proposition 2, more information and higher investment complement in production. And so we can identify two reasons why one might expect more value added 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 may often only identify a restricted equilibrium. Ex-post sorting product to ensure reliability is costly. It may be possible to substitute out 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 to seeking an ex-ante solution. The information that allowed for the ex-post sorting solution will surely be of assistance in developing an ex-ante sorting solution.

Propositions 2 and 3 bears contrasting with the analysis in Hennessy, 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 on the part of the producer, and so the producer-level incentives to make an investment that would upgrade the quality of product (i.e., raw material going into processing). 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 pointed out by Bogetoft, so would ex-ante contracts with sufficiently high-powered incentives.

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12. A related issue has been studied in Athey, where the context is a signal-contingent investment by a risk averse firm.
structures.

In our model, there need not be information asymmetry. But the existence of information asymmetry about materials coming from farms can be reflected by a shift \( \{i+1\} - \{i\} \) along the filtration so that the processor receives a less informative signal. Then, by Proposition 3, less value adding will tend to occur. 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 that the grower can credibly provide, the larger the realized reward will likely be when surplus from value added is 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 plain vanilla products.

Case Study: Soybean Product Development

Arguably, soybean has been the most aggressively developed field crop through the 20\(^{th}\) Century. While soybean products have comprised part of the staple diet in East Asia since ancient times, demand elsewhere did not become significant until circa 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). Between 1910 and 1920, and after extensive product development experimentation, soap and paint manufacturers propelled a growing import 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 soyflour as an ingredient in such items as ice creams, candies, breads, confectionaries, and
prepared mixes (Windish, p. 99). At about this time too industrial uses of crop products began to languish, being replaced by petroleum derivatives. Comparatively, soybean products performed inconsistently and were more susceptible to contamination (Myers; Hammond).

Nonetheless, crop utilization had gained traction in feed and food markets. Global production grew from 12 mill. tons, mostly in China, in the mid 1930s to surpass 100 mill. tons in the late 1980s with the majority being harvested in the U.S. (den Boer). Product and varietal development programs at Archer-Daniels-Midland and at Land Grant Universities, particularly the University of Illinois, underpinned the growth in U.S. production and global consumption (Windish). Being an annual crop, it lends itself more readily to genetic innovations than oil crops from trees (Hammond). Compared with other annual oilseed crops, the soybean’s innate versatility has encouraged the speculative research that is required to extend the filtration of \( \sigma \)-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 caused by lipoxygenase isozymes (Narvel), and undertakings to reliably use highly saturated soybean oil in the production of trans-free margarine (Kok). Instability, for example under oxidation, and other performance inconsistencies remain a major problem in penetrating industrial markets (Hammond), and are a significant area of product development research (e.g., Jiang; Ruger).

**Heterogeneity and a Set Theoretic Approach to Product Development**

The intent of this section is quite didactic in that it will outline an approach to framing sorting technologies within the standard dual cost paradigm. A processor must make decisions about where in product attribute space she wishes to locate her product. The dimensions at issue might include food safety, color, texture, fiber content, or cooking traits. Let us assume that attribute space can be completely characterized by an \( m \)-tuple of cardinal indices in \( \mathbb{R}^m \). Putting aside the heterogeneous raw materials input, the inputs available to develop any such products may be represented as a conventional input vector \( \tilde{x} \in \mathbb{R}^r \). The set representation of the heterogeneous
raw materials requires some careful characterization because we seek to capture the information environment that the processor works in.

Let there be $h$ herds of equal size and comprised of animals of $n$ distinct genetic types, where the index basis for the $i^{th}$ type is given by $\vec{e}_i$. This is a vector with zero coordinates except for a 1 at the $i^{th}$ coordinate. An herd with share $\mu_i$ of the $i^{th}$ type may be depicted then by $\vec{u} = (u_1, u_2, \ldots, u_n), u_i \geq 0, \sum_{i=1}^{n} u_i = 1$. This convex set in $\mathbb{R}_{+}^{n-1}$ is a simplex, identified as ‘Simp’.

Describe the heterogeneity status of the aggregate of herds available to the processor by the sets of points on the simplex, i.e., with reference to a basis. In particular, if $h_i$ herds of homogeneous type $\vec{e}_i$ are available, $i = 1, 2, \ldots, n, \sum_{i=1}^{n} h_i = h$, then write $B = B_{\text{sort}} = \{(h_1, \vec{e}_1), (h_2, \vec{e}_2), \ldots, (h_n, \vec{e}_n)\}$ where $B$ might be thought of as the raw materials base. In the case of $B_{\text{sort}}$, the base is said to be completely sorted and the ex-post sorting problem need not be contemplated.

Instead all these same herds might be completely mixed, say in the spot market, so that information on their types is lost. Then the characterization would be $B = B_{\text{mix}} = \{(h, \vec{u})\}$ with $\vec{u} = (h_1/h, h_2/h, \ldots, h_n/h) = (u_1, u_2, \ldots, u_n)$. Representation $\{(h, \vec{u})\}$ may be read as the statement that all $h$ herds are of composition $\vec{u}$ where fraction $u_i$ per herd are of type $\vec{e}_i$. Or it may be read as the statement that information about sorted herds has been lost before the processor has gained control of the raw materials, but that the processor is rational in expectations in discerning the composition of the raw materials. This mixing of types will be difficult to reverse because, even if it were feasible and costless to sort ex-post, information acquisition costs would have to be incurred. In equilibrium, it may not be efficient to sort a mixed aggregate.

Now we identify the attribute possibility set as the correspondence $Z(\vec{x}, B) : \mathbb{R}^r \times \{\text{Simp}\}^h \rightarrow \mathbb{R}^m$ where the second argument describing the set is understood to be a set of $h$ points on Simp. The set is assumed to adhere to

**Assumption 4.** Set $Z(\vec{x}, B)$ satisfies the properties: a) closed and nonempty,
b) monotone weakly larger in $\vec{x}$, i.e., $Z(\vec{x}', B) \supseteq Z(\vec{x}, B) \quad \forall \vec{x}' \succeq \vec{x}, \forall B \in \{\text{Simp}\}^h$ where vector ordering $\succeq$ is understood to be the usual coordinate-wise ordering,
Assumptions a) and b) are standard in production theory (Chambers). Assumption c) merely asserts that any characteristic vector attainable with vector \( \bar{x} \) of the ‘usual’ inputs and an heterogeneous raw materials vector can also be attained under the same vector of the usual inputs but where the raw materials vector has been sorted to be homogeneous. This too seems to be an acceptable assumption because product can generally be readily mixed whereas sorting is a much more involved endeavor. Being somewhat cavalier with terminology from linear algebra, the attribute opportunities afforded by a disaggregation of the raw materials span the opportunities afforded by the heterogeneous aggregate. But it should be remembered that set \( Z(\bar{x},B) \) cannot be treated as a vector space. Quite apart from the distinction that the objects are sets rather than points, part c) shows that the sets are not necessarily linear in the sense that vector spaces are linear. The attribute possibility sets associated with \( \bar{x} \) and the \( B_i \), with given \( h \) value and where \( B_i = \{(h_i, \bar{e}_i)\} \), cannot be used as a vector basis for representing any attribute possibility set.

Now let \( \bar{w} \in \mathbb{R}^p \) be the price vector for regular inputs. Write the minimized unit cost of attaining \( \bar{z} \), given \( \bar{w} \) and raw materials base \( B \), as \( C(\bar{w},\bar{z},B) \). Standard arguments then deliver Proposition 4. If Assumptions 3 and 4 are valid, then \( C(\bar{w},\bar{z},B_{\text{sort}}) \preceq C(\bar{w},\bar{z},B_{\text{mix}}) \) \( \forall \bar{w} \geq 0 \), \( \forall \bar{z} \in \mathbb{R}^m \).

The result asserts that an ex-ante sorted raw materials base is to be preferred, and that an absence of information allowing costless sorting into homogeneous lots is in some sense constraining. Sorting has value in that it can reduce the cost of products that had been feasible under heterogeneity, and it can also make feasible erstwhile infeasible products.

**Genetics, Information Management, and the Dynamics of Productivity**

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 sectors in U.S. agriculture. The role of innovation in the industrial evolution of firms over time has not received the attention it deserves in the Industrial Organization literature. The seminal formal work to explain Schumpeter’s famous thesis on firm evolution in a dynamic framework is due to Nelson and Winter. Two of their theoretical findings are relevant to the present study: (1) firms that experiment (innovate) grow relative to firms that imitate, and smaller firms disappear; (2) 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 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 bottle-neck in adjustment toward lower unit costs. 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 the production or processing stages, genetic non-uniformities likely impede throughput and so, consistent with the arguments of Allen and Lueck, may support a more labor-intensive approach to production.

The arguments are developed in four sub-sections. The first motivates the later parts through reference to the recent history of the poultry sector and opinions of professionals in that sector. The next three model processing and production efficiencies which arise from uniformities and that are alluded to by commentators on the industry. The final sub-section eyes changes in the hog sector with reference to the poultry sector and to economic perspectives on structural dynamics.
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 among the shorter and more rapidly maturing. Poultry and egg production had been highly fragmented until the 1920s (Schwartz; Bugos). Indeed, the advent of the commercial broiler industry in the U.S. is often credited to Mrs. Wilmer 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 already just begun its journey towards industrialization. Mrs. Steele sold her young laying flock as meat, making a tidy 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 U.S. 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 untapping industry cost and revenue potential was the discovery of insights that allowed 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. On the processing side uniformity facilitated automation, in deboning for example (Schwartz; Government

13. Most of the materials in this section report facts and opinions in Bugos, in Schwartz, and in Roberts.

14. These two themes may be linked. Rapid productivity improvements in a few traits are often achieved at the expense of other traits. As a consequence, productive animals may be more sickly. Sickly creatures need more attentive husbandry unless the herd is relatively homogeneous. 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.
Accounting Office). 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. And, as we will argue, greater consistency may also 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 pure-bred 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 due to hybrid vigor. And, for breeding companies, the hybridization approach provided the additional benefit of a natural protection for intellectual property because the sold bird could not be used to replicate consistently.

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 2 provides data on U.S. poultry, pork, and beef consumption and prices over the years 1930 through 1997. 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 price or hog price. For example, the relative price of broilers declined by about 2.6% per year over 1940-’97 when the comparison is relative to hog prices. While not as dramatic, the decline relative to the hog price was 1.2% over 1960-’97. The rise of the 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.

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 gain (Bugos). By 1994, 37 day broilers weighed about 1.7 Kg, while feed conversion efficiency was about 1.65 Kg feed per Kg gain to 37 days (Nicolson). As to product differentiation, it is believed by some observers that poultrymeat is about 20 years ahead of other meats in tailoring products to value-added consumer sub-markets (Kilman). Referring to attempts by beef packers to replicate the success of poultry processors in meat market penetration, Kilman wrote in January 2001:

"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 preparation 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. . . . . IBP also is launching a line of fresh beef and pork under the Wilson name. To do this, the company is having its employees sort through cuts more carefully to come up with a consistent product."

This quote points to the possibility of a sorting premium to be extracted at the point of retail. But sorting premia may also arise elsewhere. In the example below, we identify a sorting premium that arises in processing.

**An Environment with Positive Sorting Premium**

The broiler industry places much emphasis on uniformity in production. This is true of feed, medication, and animals at the grow-out stage, where integrators typically require the grower to obtain these inputs from a central source (Tsoulouhas and Vukina). And the application of

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15. For an interesting discussion on poultry sector product development, see Hudspeth.

16. Tyson, a poultry processor, was then negotiating an agreement to purchase IBP, a beef and hog packing company. Also, Amana Beef Products, Amana IA, has engaged in hand selection off the production line for it’s line of premium cuts.

17. A variety of factors may motive the integrator, and determine what is integrated. In poultry and hogs, early stage integrators have tended to be feed companies, and the intent would appear to be to achieve production-stage scale economies. Some time later, processors take an interest in further integration. Concerns about excessive genetic homogeneity and disease susceptibility would appear to be important in determining that breeders retain autonomy. Legacy production assets, local politics, property rights
inputs is often stipulated in production contracts. For housing, too, the integrator often seeks to specify the type of building used. On the processing side, uniformity has facilitated automation; in deboning for example (Schwartz; Government Accounting Office). In the brief model to follow, we will identify a coordination premium arising from such uniformity.

Consider an operation where batches of a given stock of raw materials are to be processed. Each of $S$ batches, $s \in \{1, 2, \ldots, S\}$, is comprised of $m$ units and each unit $i \in \{1, 2, \ldots, m\}$, requires a processing time of $t_{s,i}$. The technology is fixed in that it is not conditioned on how the given stock of raw materials is partitioned into batches. The time for a batch to be processed is given in a Leontief manner by the largest $t_{s,i}$ among the batch. Total time taken to process the product is given by the sum of batch times, which we write as

\[ \mathcal{D}_\pi = \sum_{s=1}^{S} \text{Max}[t_{s,1}, t_{s,2}, \ldots, t_{s,n}] . \]

Here the subscripted symbol $\pi$ identifies the particular arrangement of the batches. This is just one among the $(mS)!/(m!)^S$ arrangements of $m$ units into $S$ batches. We label the set of all possible batch arrangements as $\Pi$. Suppose now that the units are sorted, and we label the $mS$ units in increasing order according to time taken for processing. Unit $(i)$ has processing time $t_{(i)}$ so that $t_{(1)} \leq t_{(2)} \leq \ldots \leq t_{(mS)}$. Define partition $\hat{\pi}$, which we call the full sorting partition, as the ordered partition with batches $\{(t_{(1)}, t_{(2)}, \ldots, t_{(m)}), (t_{(m+1)}, t_{(m+2)}, \ldots, t_{(2m)}), (t_{(3m-m+1)}, t_{(3m-m+2)}, \ldots, t_{(3m)})\}$. Of course, such sorting must be supported by the existing information environment concerning the units.

In particular, complete information on raw material types, together with zero sorting costs, would make the full sorting partition feasible. This sorting partition is of interest because it has been demonstrated by Minc that incentives issues (Hart and Moore), and perhaps access to subsidized capital sources may motivate grower autonomy in the evolving production structure.
\[ \mathcal{L}_k = \min_{\pi \in \Pi} \mathcal{L}_\pi. \]

And so we have

**Proposition 5.** *For a processing technology that is Leontief and fixed, the full sorting partition of raw materials minimizes processing time.*

It bears emphasis that the processor has not been allowed to condition the technology to the batch. Were this possible, then the finding in Proposition 5 would likely be re-inforced in practice because it would likely be easier to condition the technology to a relatively homogeneous batch than an heterogeneous batch.

All the arguments laid out thus far have been static in that technical change does not depend on the composition of raw materials. In the model to follow we show one pathway through which sorted herds facilitate the rate of learning about the nature of technologies, and so the temporal rate of expansion of opportunity sets. The argument is somewhat subtle, and so we will devote some space to explaining and motivating both our approach and our inferences. In particular, as points of reference we will consider the evolution of the U.S. poultry and hog sectors.

**Incentives to Learn**

Environmental control has always been recognized as a significant factor in determining (static) producer performance (see, e.g., Lacey or Ritchie). Perhaps more important, however, are the implications of a controlled environment for dynamic performance, and the conditions of poultry farms are well suited for experimentation. In the typical poultry production contract in the U.S., 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 has opined

"However, 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 industry to avoid transactions costs impediments to gleaning better technical and economic performance from the livestock, industry structure was important for dynamic process-related reasons as well. 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.

Let the aggregate property to be managed, in this case a flock or herd, be composed of \( n \) genetic types labeled 1 through \( n \). Fraction \( a_i \geq 0 \) 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 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, i.e., without interfering with one-another. Variable \( b \in [b,\overline{b}] \) is an index of projects, and \( q \) is the level of output at the entrepreneur’s firm. The ranking gives \( g(b;\kappa,q,\eta T) > 0 \). Parameter \( \kappa \) is an index of curiosity (or serendipity) in assembling these conjectures, and we assume that the more curious operator has collected a stronger portfolio of conjectures so that \( g_0(b;\kappa,q,\eta T) > 0 \). It is also assumed that the potential increases with \( q \) because innovations can be leveraged over larger volumes of output. Variable \( \eta \) is non-negative and random, reflecting the consequences of

18. Of course, from the perspective of optimizing in a static environment, control is a precursor for the capacity to optimize over the control variable. Housing often provides the opportunity to control. Dahl reviews the literature on manipulating light exposure to optimize commercial bovine milk production.

19. In a less formal framework, and concerning product design projects, Thomke provides interesting discussions on process engineering to take advantage of technological innovations that reduce the costs of experimentation.
uncontrolled aspects of the production environment per unit time. Variable \( T \) is the age at slaughter so that \( \eta T \) is a measure of cumulative randomness in the general production environment over the duration of the production process.\(^{20}\) We hold that \( g(b; \kappa, q, \eta T) \) is decreasing and concave in argument \( \eta T \) so that the marginal impact of random adverse production shocks becomes more severe as the level of \( \eta T \) increases.

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 \( \varepsilon_{i,b} \), \( i \in \{1, 2, \ldots, n\} \) 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 her business will be subjected to a profit impact of \( \bar{a} \cdot \bar{e}_b \) if the index of potential is omitted. Here \( \bar{a} \cdot \bar{e}_b = \sum_{i=1}^{n} a_i \varepsilon_{i,b} \). The index enters in a multiplicative manner, so that the profit impact of the one-time implementation is \( g(b; \kappa, q, \eta T) \bar{a} \cdot \bar{e}_b \). Random variable \( \eta \) is held to be independent of \( \bar{e}_b \), and an experiment conducted will only be introduced if it improves profit, i.e., if \( \text{Max}[\bar{a} \cdot \bar{e}_b, 0] \geq 0 \). Each experiment requires sunk cost \( c > 0 \), and the discount rate per unit 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 the appropriate discount rate increases linearly with age at slaughter, \( rT \).

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

\[
(8) \quad Y(b; a, \kappa, q, c, T) = \frac{E\{g(b; \kappa, q, \eta T)\} E\{\text{Max}[\bar{a} \cdot \bar{e}_b, 0]\}}{rT} - c,
\]

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

\[^{20}\text{One might think of } \eta T \text{ as being the out-turn of a continuous-time stochastic process such as geometric Brownian motion.}\]
implicitly a function of the other arguments of \( Y(\cdot) \) in (8). If the weighting measure on \([b, \bar{b}]\) is \( \varphi(A) \) for \( A \subset [b, \bar{b}] \), then the measure of implemented projects is \( \varphi([b^*, \bar{b}]) \). A comment is warranted concerning the appropriateness of objective function (8). It assumes that the firm cannot easy-ride 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 \( \bar{e}_b \) 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 \( \bar{e}_b \) 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 \( \bar{e}_b \) are exchangeable.\(^{21}\) For exchangeable random variables, it is well-known among mathematical statisticians that function \( E\{\text{Max}[\bar{a} \cdot \bar{e}_b, 0]\} \) is symmetric and convex in \( \bar{a} \) (See, e.g., Marshall and Olkin, pp. 287–288). Therefore, the function is Schur-convex. This means that function \( E\{\text{Max}[\bar{a} \cdot \bar{e}_b, 0]\} \) is larger under \( \bar{a}'' \) than under \( \bar{a}' \) whenever \( \bar{a}'' \) majorizes \( \bar{a}' \).

**Definition 3.** (See Marshall and Olkin, 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 \( \bar{u} < \bar{v} \) if

a) \( \sum_{k=1}^{l} u_{[k]} \leq \sum_{k=1}^{l} v_{[k]} \) \( \forall k \in \{1, 2, \ldots, n-1\} \), 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, \((\frac{\gamma}{8}, \frac{\gamma}{8}, \frac{\gamma}{2}) < (0, \frac{\gamma}{8}, \frac{\gamma}{8})\) because \( \frac{\gamma}{2} \leq \frac{\gamma}{8}, \frac{\gamma}{8} \leq 1, \) and \( 1 = 1 \). We will have particular interest in the extremes of the majorization relation;

\[
(9) \quad \left( n^{-1}, \ldots, n^{-1} \right) < \left( a_1, \ldots, a_n \right) < (1, 0, \ldots, 0)
\]

for any \( \bar{a} \) with nonnegative components and on the unit simplex, i.e., \( \bar{a} \cdot \bar{1} = 1 \).

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

\(^{21}\) Consider the distribution function \( F(x_1, x_2, \ldots, x_n) \) for some vector \( \bar{x} \). The random variables are exchangeable if the value of \( F(x_1, x_2, \ldots, x_n) \) 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.
**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 map \( \bar{a}' - a' \in \mathbb{R} \) whereby \( \bar{a}' \prec \bar{a}'' \Leftrightarrow a' < a'' \).

**Proposition 6.** (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 \( \bar{a}'' = (1, 0, \ldots, 0) \), which could be interpreted as a cloned aggregate. This would elicit the largest level of experimentation. On occasion too, natural experiments may occur whereby an irregularity arises at some production unit. If the unit happens to perform well relative to the controlled units, then the irregularity gives rise to a conjecture. While the conjecture arose due to an uncontrolled event, it should be noted that the event might give rise to a conjecture because the event can be compared with performance in a controlled environment. The consequences of an irregularity are unlikely to stand out when compared with a noise-filled environment. A second 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 may occasionally arise from fundamental research.

The economics underpinning part (a) bear comparison with the concept of an economic tournament, a common remunerations structure in poultry production (Knoeber). Economic tournaments, if thoughtfully constructed, shift the shared performance risks of participants onto the contractor. By removing this noise, performance incentives can be sharpened. Likewise, the
removal of background noise allows for sharpened 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 \( a \) will also likely affect the flow of conjectures. Ideas to work on 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, will likely have this effect. This is because the entrepreneur will be more sure that events other than those arising in the experiment did not affect the out-turn of events.

Proposition 6 provides an explanation as to why the characteristics of poultry production assumed an industrial nature before approaches taken in the production activities for later maturing livestock. As \( T \) declines, the rate of experimentation picks up. An assembly-line approach is only possible 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 \( \kappa \) changes.

**Proposition 7.** Assume that \( b \) is uniformly distributed on \([\underline{b}, \overline{b}]\).

i) 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.

ii) 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. Single crossing conditions can also be constructed where a stochastic change in $\eta$ replaces the change in $a$. For example, an index representing a mean-preserving spread in $\eta$ would replace $a$ in the proposition. Notice that the uniformity of $b$ across $[\bar{b}, \bar{b}]$ is important in Proposition 7. 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.

**Dynamic Consequences**

At this point we turn to implications for structure. We will employ a competitive markets learning-by-doing model in the manner of Fudenberg and Tirole to capture the effect of learning on structure. The producer that experiments learns by doing. A fixed number of firms, labeled $i = 1, 2, \ldots, m$, produce an homogeneous good over two time periods, I and II, where II is later than I. Costs in period I are given by the increasing and convex firm-specific function $C^i_I(q^i_I)$. In period II the firm’s costs are given by $C^i_{II}(q^i_{II}; v^i_I)$ where the function is increasing and convex in the first argument but decreasing in the second argument. Parameter $v^i_I$ is the firm-specific learning index which we hold to be increasing in indices $a$ and $\kappa$ from Proposition 6. Further, period II marginal costs are also decreasing in the second argument. The inverse demand function, $P(Q)$, is common across periods, where aggregate output is given by $Q^I = \sum_{i=1}^{m} q^i_I$ in period I and $Q^{II} = \sum_{i=1}^{m} q^i_{II}$ in period II. With discount factor $\delta$, the firm faces present value function

$$W = P(Q^I)q^I_I - C^i_I(q^i_I) + \delta P(Q^{II})q^i_{II} - \delta C^i_{II}(q^i_{II}; v^i_I).$$

In a rational expectations equilibrium, producers in period I will recognize the cost

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22. From Proposition 6, learning parameter $v^i_I$ also depends on the level of firm output. But we do not consider this effect here because it brings to the fore the possibility of multiple equilibria. Treatment of multiple equilibria would not add to model insights except to reveal that the equilibrium response to, say, an infinitesimal increase in $a$ may be discontinuously large.
efficiencies to be achieved through learning. And they will also recognize that other firms will do the same such that price will be driven down in period II. The first-order conditions when each firm acts competitively are

\[
P(Q^I) - \frac{dC^{i,I}(q^I_i)}{dq^I_i} - \delta v_i \frac{dC^{i,II}(q^I_i; v^I_i q^I_i)}{dv^I_i q^I_i} = 0,
\]

(11A)

\[
P(Q^II) - \frac{dC^{i,II}(q^I_i; v^I_i q^I_i)}{dq^I_i} = 0.
\]

(11B)

Consider (11B) first. The learning effect pushes marginal costs down, and adjustments will occur on the supply side where firm-level output rises as well as on the demand side where period II price falls. In (11A), the learning term pushes effective marginal costs down, thus likely encouraging production in period I also.

To obtain an explicit rational expectations solution, suppose that the demand function is linear, \( P(Q^k) = \alpha_0 - \alpha_1 Q^k, \ k \in \{1, 2\} \). Let the \( v_i \) be common, say \( v \). And let the period I cost function be common to all firms and quadratic in form, \( C^I(q^I_i) = \beta_0^I + \beta_1^I q^I_i + \frac{1}{2} \beta_2^I (q^I_i)^2 \), \( \beta_0^I > 0 \), \( \beta_1^I > 0 \), \( \beta_2^I > 0 \). In period II, fixed costs fall relative to period I by the magnitude \( \nu^I \lambda q^I_1 \), \( \lambda > 0 \), and marginal costs fall by magnitude \( \nu^I \lambda_1 q^I_1 \), \( \lambda_1 > 0 \), so that period II costs can be represented by \( C^{II}(q^I_i; v^I_i q^I_i) = \beta_0^I + \beta_1^I q^I_i^I + \frac{1}{2} \beta_2^I (q^I_i^I)^2 - \nu^I \lambda_0 q^I_i - \nu^I \lambda_1 q^I_i q^I_i^I \). Assume that \( \alpha_0 > \beta_1 \) and that \( v \) is sufficiently small to support a finite solution. Solving (11) for the identical firms, we have
\[
q_I = \frac{(\alpha_1 m + \beta_2)(\alpha_0 - \beta_1 + \delta v \lambda_0) + (\alpha_0 - \beta_1) v \delta \lambda_1}{(\alpha_1 m + \beta_2)^2 - \delta v^2 \lambda_1^2} \quad \forall i \in \{1, \ldots, m\},
\]

\[
q_{II} = \frac{(\alpha_1 m + \beta_2)(\alpha_0 - \beta_1) + (\alpha_0 - \beta_1 + \delta v \lambda_0) v \lambda_1}{(\alpha_1 m + \beta_2)^2 - \delta v^2 \lambda_1^2} \quad \forall i \in \{1, \ldots, m\}.
\]

It is readily seen that both quantities are increasing in learning parameter \(v\). Some algebra reveals that \(q_I < q_{II}\) is not assured. The inequality is more likely if the value of \(\delta\) is small or if demand-side responsiveness, as measured by \(\alpha_1 m\), is small or if the marginal gain from learning-by-doing, as measured by \(\lambda_1 v - \beta_2\), is large.

**Hog Sector**

Hogs for meat in the U.S. 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 6 suggests that hogs, if at all, should undergo industrialization after poultry but before cattle. This theory is broadly supported by the evidence (Ritchie). Beef production at the later stages is now overwhelmingly (85-90%) 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 1980's. Consolidation in the pork industry is occurring at a rapid pace. In 1988, 32 percent of hogs marketed came from operations producing less that 1,000 head per year, and 7 percent from operations over 50,000 head.\(^{23}\) By 1997, only 5 percent came from 80,000 operations marketing less than 1,000 head per year and 37 percent from 145 operations marketing over 50,000 head each. In 1994, the top 5 producers owned about 8 percent

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\(^{23}\) The following estimates are based on *Successful Farming* Online, October 1999, Lawrence *et al.*, and National Agricultural Statistics Service, *Hogs and Pigs*, various issues online.
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, and the top 25 owned 34 percent of the breeding herd. Further, much of the integration that is occurring is vertical. By 2001 the top producer, Smithfield, and 5 of the top 10 producers were meat packing companies.

Important gains in efficiency have been achieved through genetics, large-scale hybridization, and artificial insemination. Pigs per litter have increased 13 percent from 7.86 in 1989 to 8.86 in 1999. Litters per sow also increasing, and the pounds of pork produced per sow in the breeding herd has increased 27 percent from 1989 to 1999. Similar to poultry, significant increases in feed efficiency have been realized as well.²⁴ Little progress has yet been made in reducing days to market (i.e., unlike broilers), because selecting for lean meat often requires selecting against improved rate of gain and because pigs are being slaughtered at heavier weights.

From our observations, it is evident that structural changes are underway in the pork industry that parallel the broiler industry. In part, these changes are facilitated by increased genetic standardization, which helps create an environment conducive to experimenting.²⁵ New production technologies, biased toward larger, more coordinated production processes, have also 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 electronic 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 so likely enhance the learning environment.

As reported in Onishi et al., clones of mature pigs were farrowed in July 2000. Mature sheep,

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²⁴ Based on the Iowa Swine Enterprise Records Program participants, feed efficiency has gone from 4.1 pounds feed/pound gain in 1979 to 3.8 pounds in 1989 to 3.5 pounds in 1999 for farrow-to-finish operations.

²⁵ By 2001, just 10 companies accounted for the majority of genetic seedstock marketed by swine companies (Ritchie).
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 these innovations 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. Quite distinct from the ability to better meet consumer tastes, we have also shown how information on raw materials can have logistical value for a processor. And we suggest a third, inherently 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

Conclusion

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amounts of 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 would seem to be important that the implications of these innovations for the nature of food production be well thought through.
Appendix

Proof of Proposition 3. Fix the value of $K$, and consider $V[\mathcal{F}_0(K)]$ so that only product A is produced. Now, from Proposition 1, $V[\mathcal{F}(K)]$ is monotone in $\{i\}$ for any value of $K$. Define $G^*\{\{i\}\} = \max_{K} V[\mathcal{F}(K)] - K$. If $G^*\{\{i\}\} > G^*\{\{0\}\}$ then both A and B must be produced, for otherwise $G^*\{\{i\}\} = G^*\{\{0\}\}$. Because Proposition 1 asserts that $G^*\{\{i+1\}\} = G^*\{\{i\}\}$, if $G^*\{\{i\}\} > G^*\{\{0\}\}$ then both A and B must be produced under $\{i+1\}$ too. 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., $\{\omega(K): \omega(K) \geq \delta/L\}$ has null measure for some $K \in \mathbb{R}$, and yet $\omega_0(K) = E[\omega_0(K)|\mathcal{F}_0(K)] = \delta/L$ where $\omega_0(K)$ is bounded. \hfill\Box

Proof of Proposition 4. By Assumption 4c), if $\tilde{z} \in Z(\tilde{x},B_{mix})$ then $\tilde{z} \in Z(\tilde{x},B_{sort})$. Using Assumption 4b), for $\tilde{z} \in Z(\tilde{x},B_{mix})$ there exists an $\tilde{x}^*$ with $\tilde{x}^* \leq \tilde{x}$ such that $\tilde{z} \in Z(\tilde{x},B_{sort})$. With $C(\tilde{w},\tilde{z},B) = \min_{\tilde{x}} \{\tilde{w} \cdot \tilde{x}: \tilde{z} \in Z(\tilde{x},B)\}$, the Weierstrass theorem together with Assumption 4a), a standard 'bounding' operation and the continuity of $\tilde{w} \cdot \tilde{x}$ in regular inputs gives the result. \hfill\Box

Proof of Proposition 6. For part (a), we will demonstrate the result for index $a$ and for slaughter date $T$. The other effects can be shown similarly. From the definition, together with the Schur-convexity of function $E\{\max[a \cdot \tilde{e}_b, 0]\}$, we have $a' < a'' \Rightarrow E\{\max[a' \cdot \tilde{e}_b, 0]\} \leq E\{\max[a'' \cdot \tilde{e}_b, 0]\}$. Fix parameters other than $a$ and $b$. Remembering that the distribution from which $\tilde{e}_b$ 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 Eqn. (8) increases as $T$ increases. Concerning the numerator, we have $dE \{ g(\cdot) \}/dT = E\{ \eta dg(\cdot)/d(\eta T) \} = E\{ \eta \} E\{ dg(\cdot)/d(\eta T) \} + \text{Cov}(\eta, dg(\cdot)/d(\eta T)) \leq 0$. The inequality is due to the decreasing and concave properties of $g(\cdot)$ in $\eta T$. Given $g_b(\cdot) > 0$, it follows that $db^*/dT > 0$ and the measure of experiments engaged in declines with the age to slaughter because set $[b^*, \tilde{b}]$ contracts. \hfill\Box
Proof of Proposition 7. 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 $\kappa$, 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 experiments engaged in 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 ii), write $r(b) = E\{g(b;\kappa,q,\eta,T)\}$ and $s(a) = E\{\text{Max}[\bar{a}\cdot\bar{\epsilon}_b,0]\}$. Note that if $c$ increases then $b^*$ increases to restore equality in (1). 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 $[r^2(b) - r(b)r_{bb}(b)]$, 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. □
References


Knoeber, C. R. "A Real Game of Chicken: Contracts, Tournaments, and the Production of..."


11 and p. 13.


Table 1. Matrix Classification of Sources of Demand for Agricultural Product Information

<table>
<thead>
<tr>
<th>Concerned party</th>
<th>Grower</th>
<th>Processor</th>
<th>Consumer</th>
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<tbody>
<tr>
<td>Information type</td>
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<td>G1</td>
<td>G2</td>
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<tr>
<td>Genetic</td>
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<td>herd homogeneity, genetic lines</td>
<td>genetic engineering status; mean genetic quality; sorting efficiencies; consistency and reliability for value adding</td>
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<tr>
<td>Non-Genetic</td>
<td>N1</td>
<td>origin, organic status, and disease status of animal, feed, and seed inputs</td>
<td>N2</td>
</tr>
<tr>
<td></td>
<td>origin of raw materials; production practices used at grower level; consistency, reliability, and texture of raw materials</td>
<td>animal welfare during production; feed used; food safety; age at slaughter (veal)</td>
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Table 2. Animal Production and Prices, U.S., 1930-1997

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<tr>
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<tbody>
<tr>
<td>Quantity (Mil lbs)¹</td>
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<td></td>
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<tr>
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<td>2158</td>
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<td>1185</td>
<td>1178</td>
<td>1065⁸</td>
<td>1038⁸</td>
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<td>6017</td>
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<td>15,538</td>
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<td>37,523³</td>
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<td>17,043</td>
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<td>21,185</td>
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<td>39,521</td>
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<td>39,202</td>
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<td>74.60</td>
<td>63.10</td>
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</table>

Source: Agricultural Statistics, USDA - National Agricultural Statistics Service, various issues

¹ Liveweight
² 97 mill. lbs to broilers were reported in 1934 at price 19.3¢/lb.
³ Ready to cook equivalent broilers was 27,041 mill. lbs.
⁴ Carcass weight equivalent to hogs was 17,274 mill. lbs.
⁵ Carcass weight equivalent to cattle was 25,490 mill. lbs.
⁶ Reported as ¢/lb.
⁷ Not included in farm production of chickens.
⁸ Estimated from ready to cook production (×2.036).