Complementarity in Organizations

Erik Brynjolfsson* and Paul Milgrom**

August, 2008; Revised, December, 2010 and January, 2012.

Draft chapter for Handbook of Organizational Economics

*MIT Sloan School and the NBER       ** Stanford Department of Economics

We thank Josh Mollner, Shachar Reichman and Adam Saunders for providing useful research assistance, Bob Gibbons and John Roberts for helpful comments, and the National Science Foundation (IIS-0085725 and ITR-0427770) and the MIT Center for Digital Business for research support.
1 Introduction

According to the *American Heritage* dictionary, a *synergy* is “the interaction of two or more agents or forces so that their combined effect is greater than the sum of their individual effects” or “cooperative interaction among groups, especially among the acquired subsidiaries or merged parts of a corporation, that creates an enhanced combined effect.” “Complementarity,” as we use the term, is a near synonym for “synergy,” but set in a decision-making context and defined below with mathematical precision.

Complementarity is an important concept in organizational analysis because it offers an approach to explaining patterns of organizational practices, how they fit with particular business strategies, and why different organizations choose different patterns and strategies. The formal analysis of complementarity is based on studying the interactions among pairs of inter-related decisions. For example, consider a company that is evaluating a triple of decisions: 1) Whether to adopt a strategy that requires implementing frequent changes in its technology, 2) Whether to invest in a flexibly trained workforce, and 3) Whether to give workers more discretion in the organization of their work. Suppose that more flexibly trained workers can make better use of discretion and that more flexibly trained and more autonomous workers make it easier to implement new technologies effectively, because workers are more likely to know what to do and how to solve problems. Then, there is a complementarity between several pairs of decisions, which is characteristic of a system of complements. The theory of
Complementarities predicts that these practices will tend to cluster. An organization with one of the practices is more likely to have the others as well. Suppose an organization employs these three practices. Should this organization now adopt job protections or incentive pay, or both? The answer depends in part on the presence or absences of complementarities: if these new practices enhance worker cooperation with management in periods of technical change then they, too, should be part of the same system.

Often, there is a related environmental variable that drives an entire system. In our example, suppose the organization operates in an environment that contains frequent, substantial opportunities to upgrade technology to save costs or improve products. Then it would be natural for the organization to favor the first practice – making frequent technical changes. Because of complementarities, this would in turn favor adopting the whole group of practices described above. The clustering of practices, the way choices depend on the environment, and the influence of each practice on the profitability of the others are all empirical propositions which we summarize with our example in Table 1.

Table 1

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Make frequent technical</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>changes</td>
<td></td>
<td>+</td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Train workers flexibly</td>
<td></td>
<td></td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Give workers discretion</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Protect worker jobs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(*) Frequent opportunities to upgrade technology</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 is a prototype for portraying and discussing the interactions in a system of complements. Each decision about a particular practice is labeled and appears in both a row and a column. We put the environmental variables in the rows below the double line. In this case, there is just one: the frequency of valuable opportunities to upgrade
Complementarity in Organizations

technologies. To verify the system of complements, it suffices to check just the upper half of the table because the complementarity relation is symmetric. Also, we can omit checking the diagonal entries because complementarity is defined in terms of interactions between different decisions. (The entries that don’t need to be checked are shaded in grey.) The pluses in cells (1,2) and (1,3) of the Table represent the complementarities that we have hypothesized are present between frequent technical changes and two other labor practices, while the plus in cell (2,3) represents our hypothesis that flexibly trained workers use discretion more effectively. Worker protection aligns worker’s long-term interests more closely with the firm’s interest, reducing resistance to change and enlisting workers in implementation. That accounts for the pluses in cells (1,4) and (3,4).

The plus in the last row indicates that the environmental variable directly favors one of the choices and, through the system of complements, indirectly favors all of the others. We leave the cells blank when a priori we do not believe there to be a direct interaction. A version of this tool, called the Matrix of Change, has been used by managers and MBA students to analyze complementarities and thereby assess the feasible, pace, scope and location of organizational change efforts (Brynjolfsson, Renshaw and Van Alstyne, 1997).

1.1 Some Applications and Implications

Complementarity ideas can be usefully combined with ideas about the limits to coordination among separate firms to explore the scope of the firm. For example, in the early 20th century, General Electric produced a wide array of products based on electric motors. Its intensive research into designing and producing electric motors was complementarity to its strategy of producing a broad range of products using those
motors. Improvements in the costs or capabilities of electric motors for one product line increased the probability of improvements for other products lines. Coordinating such a variety within a single firm was favored by its concurrent development of a multi-divisional organizational architecture.¹

In addition, the analysis of complementarities can provide insights into organizational dynamics. For example, even when senior executives have a clear vision of a new strategy for a company, managing the change can be difficult or impossible (e.g. Argyris, 1982; Schein, 2004, Siggelkow 2002).

Why is organizational change so difficult? Complementarities can provide part of the answer (Milgrom and Roberts, 1990, 1992, 1995; Brynjolfsson, Renshaw and Van Altyne, 1997). When there are a large number of complementarities among practices within an existing system, but conflicts between practices from the old system and practices from the new system, then it is likely that the transition will be difficult, especially when decisions are decentralized. Because of the complementarities, changing only one practice, or a small set of practices, is likely to reduce overall performance.²

The natural conclusion is that the organization should change all of the practices in the new system simultaneously. However, making the changes all at once can be difficult or infeasible for at least three reasons:

¹ There can be several explanations of why coordination is often easier within a firm than across firm boundaries. One possibility based in contract theory is that contracting on knowledge inputs is especially difficult. A second possibility based on differences in beliefs (rather than differences in information) is that GE management may have been more confident about the potential of the electric motors technology than managers in similar firms. For each of these explanations, one is led to the conclusion that GE’s role as the center for research in electric motors created a complementarity that favored its making a broader range of products.

² Performance will suffer in absolute terms when adopting practices one at a time for a particular type of complementarity: the case where the benefit from adopting a practice in isolation is negative, even when the benefit from adopting the whole bundle of practices is positive. More generally, performance will increase less than proportionately whenever the sum of the benefits of adopting isolated practices is less than the benefit from adopting them as a bundle. In other words, whenever complementarities are present.
First, there is a basic coordination problem. Actors who control different business practices, assets, markets and strategies, including some which may be outside the direct control of the firm, need to coordinate on the scope, time and content of the change. Furthermore, because the exact outcomes and optimal levels of each factor are likely to be at least partially unpredictable, they need to continue to agree to and coordinate on any additional adjustments and rent-reallocations. All this requires accurate communication and an alignment of incentives.

Second, organizations inevitably consist not only of numerous explicit, well-defined, practices and choices but also a large number that are implicit or poorly defined. These may include the “culture” of the organization and rules of thumb that employees use in completing their tasks. Employees and business partners are likely to continue to act with the same implicit mental models, assumptions and heuristics even when the explicit practices are changed. Even if changes in all the known practices are coordinated, the organization may end up worse off if the implicit practices are unchanged.

Third, even if a sufficient set of the relevant changes can be identified and defined, and all the relevant actors agree on an action plan (or the decision rights are re-assigned to a group that is in agreement), the timing of change can present difficulties. Because some variables, such as building a new plant, hiring and training new employees, developing a new brand or reputation, take time, it will be difficult to synchronize all the changes. Some will need to start earlier than others (Jovanovic and Stolyarov, 2000). Furthermore, when resources are limited and changes are costly, a firm
may not have the capacity to do everything at once, but must instead phase in the changes.

Each of these types of difficulties has distinct implications for firm and industry dynamics, favoring different subpopulations of organizational types and predicting different trajectories for technical and organizational change. For instance, if firms evolve more complex, interdependent structures over time (e.g. Baron, Burton and Hannon, 1999), then one might expect older firms to have more difficulty in adapting to rapid, unpredictable changes in the environment insofar as this would require changing more complementary practices. If other conditions are right, start-ups might thrive in dynamic or volatile industries.

Thus, the complementarities framework is suited for modeling situations where combinations of practices can lead to multiple local maxima, such as when the payoff function is discontinuous, or when the practices are discrete variables that cannot be adjusted continuously. This is characteristic of the “rugged landscapes” described by Levinthan (1997) and Rivkin (2000) where adaption and imitation can be difficult. In contrast, as noted by Roberts (2004), much of the standard economic treatment of firms assumes that performance is concave function of a set of infinitely divisible design choices, and that the constraint set is convex. Under those conditions, decision makers can experiment incrementally to gradually identify an optimal combination of practices.

The transition difficulties identified with complementarities also imply distinct managerial approaches. In some cases, it may make sense to reassign responsibilities and modularizing activities. In other cases, change may be so difficult that it is best to start fresh at a “greenfield” site or an isolated “skunkworks,” separate subsidiary or new spin-
off. Some changes may simply be too costly to pursue for an organization starting with a
given set of practices.

The insights into organizational change provided by complementarities also
illuminate the difficulties firms have in imitating successful competitors. Firms like
Lincoln Electric, Wal-Mart, or Toyota enjoyed sustained periods of high performance.
As a result, they were heavily studied by competitors, consultants and researchers, and
many of their methods were documented in great detail. Nonetheless, even when
competitors aggressively sought to imitate these methods, they did not have the same
degree of success as these market leaders. Complementarities in organizations can help
explain why. As noted by Rivkin (2000), it can be exceeding difficult to search through a
space of strategies with numerous elements that are complementary, and imitators may
suffer large penalties from even small errors in attempting to match a particular
combination of practices. Subtle complementarities can make imitation difficult even
across plants within the same firm, where the participants are working to facilitate
knowledge transfer, let alone across firm boundaries. Intel now follows a “copy-exactly”
policy when new chip fabs are built. Previously, when the company copied only those
elements of a previous fab that managers thought were important, the new fabs
experienced much lower yields for several months. Rather than try to identify and
implement each of the missing complementary elements of the coherent system, the
copy-exactly approach replicates every element of the old fab, down to the choice of
paint color and orientation of windows, regardless of whether it has any known
relationship to the chip fabrication process.
Yet another related issue is mergers and acquisitions. When two organizations are combined, each brings with it a set of explicit and implicit business methods. Complementarities within and between these systems will influence how successful such a merger is likely to be, and whether one or the other organization will need to make significant changes to avoid a decline in performance. For example, Cisco Systems, a company that engages in frequent acquisitions, has had an explicit process for changing the all the acquired firms processes to match Cisco’s. The company has employed a Director of Culture who issues “culture badges” to all employees in recognition of the complementarity of culture to the functioning of the rest of their systems.

1.2 Using Theory and Data to Study Complementarities

To define complementarity mathematically, we focus initially on the decision of a profit-maximizing firm that is considering changing one or both of two practices. The first assumption is that if it is possible to make the changes separately, it must be possible to make them together. Let $\Delta_1$ and $\Delta_2$ be the increase in profits that would result from changing either alone and let $\Delta_B$ be the increase that results from doing both together. Any of these $\Delta$’s can be positive or negative and can depend on the other choices that the firm makes. The two changes are (weakly) complementary if $\Delta_B \geq \Delta_1 + \Delta_2$, regardless of the firm’s other choices. If one or both changes involves setting the level of a variable, such as the number of workers or the amount of capital to be employed, then the relevant change is understood to be an increase in that level. For example, in the neoclassical theory of the firm, capital and labor inputs to production are complementary if the
increase in output from raising both inputs together exceeds the sum of from increasing either separately.\(^3\)

The notion of complementarity can be extended to evaluate a larger set of practices or changes. If all combinations of changes are possible, then a set of changes is complementary if each pair in the set is complementary. In practice, this means that checking complementarity involves checking the entries of a table like Table 1 above. The full formal definition in which only some combinations are possible is postponed to the next section.

From the formal definitions, there follows a set of ten theorems about systems of complements. Importantly for the applications we have in mind, the theorems depend on complementarity alone; none depend on such additional assumptions as convexity of the feasible set or concavity of the objective. Two of these are characterizations that tell us what needs to be checked to verify the complementarity relationship. One is about common mathematical structures that give rise to complementarity. The shared knowledge example described above is an important example. Another describes how the static optimum changes with parameters, giving the predictions about clustering and comparative statics. There are also dynamical implications, about how such systems evolve over time, creating momentum for a series of changes. Accordingly, long-run changes in the maximum for such a system are always larger than short-run changes. There is a result characterizing the global maximum in a system of complements as a

---

\(^3\) For a firm choosing levels of two inputs, the textbook economic definition of complements is a property of the demand function. It holds that the two inputs are complements if an increase in the price of one leads to a decrease in the demand for the other. If the firm’s technology is strictly convex so that firm’s demand at any price vector is unique and the demand function is continuous, then inputs are complements in our sense if and only if they are demand theoretic complements.
point from which no set of coherent, complementary changes is an improvement. More
strongly, starting from any position in a system of complements, at least half of the
maximum improvement by changing decisions in any arbitrary way can be achieved by
restricting attention to coherent, complementary changes.

The empirical analysis of complementarities can take several forms. Examining
or re-examining case studies through the lens of complementarities can often clarify
outcomes and behavior that would otherwise resist explanation. More formal
econometric techniques can also be used to explore complementarities. One approach
examines firms’ choices to assess theories of complementarity. Assuming that firms do
maximize profits and that prices or other conditions facing the firm change, the goal is to
test whether practices that are predicted to be complementary are shown to be so in the
choice data. One may also ask about other implications of the theory and whether those
are consistent with the data.

A second form of econometric analysis focuses on performance differences.
Suppose that organizations sometimes make mistakes that lead to variation in the sets of
choices observed by seemingly similar firms. The challenge then is to infer from the
differences in performance across organizations whether the supposedly complementary
practices actually lead to higher performance when adopted together than they do when
adopted separately.

Complementarity theory promises answers to some of the most interesting
questions about firms’ practices and characteristics. For example, focusing on the
different practices adopted for employees and independent contractors, one might ask:
Why do employees usually work with assets owned by the firm, while independent contractors usually work with their own assets?

Why do employees work exclusively for their employer during their work hours, while independent contractors more often have multiple clients and control their own work hours?

Why are employees paid by the hour while independent contractors are more often paid based on performance or “deliverables?”

Why is training typically more extensive for employees than for independent contractors?

Such clusters of practices may reflect a simple complementarity: each change from an independent contracting practice to an employment practice makes the other changes of that sort more valuable, creating a tendency for practices to be grouped in a particular way. The complementarity relation is symmetric, so the logic can also be applied in the reverse direction: each change from an employment practice to an independent contracting practice makes other changes of that sort more valuable.

Complementarities like this will make it risky for a manager to pick and choose best practices from various organizations or systems. For instance, an incentive system that leads to high performance in one context may be highly dysfunctional in a different context that lacks the supporting complementarities. Thus, complementarities can complicate learning and increase inertia, especially if they are not well understood.
2 Theory

For a precise mathematical treatment of complementarities, it is convenient to treat all the choices as numeric. Some variables we study are inherently numeric, such as levels of inventory, years of training, or commission rates for salespeople. Others are qualitative binary choices, such as the decision as to make or buy, to use an employee or a contractor, or whether to scrap a line of business. For the latter, we represent the choice as being from the set \{0,1\}, with 0 denoting what we will case the baseline decision and 1 denoting the alternative. When the variable is inherently numeric, the relevant change can be an increase or decrease, for example a switch to higher or lower levels of inventories. For the mathematical development, we assume that the baseline refers to the lower level of the variable.

With \(n\) binary choices to make, the decision maker’s payoff can be denoted by \(f(x)\), \(x \in \{0,1\}^n\), which we may also write as \(f(x_i,x_j,x_{-ij})\). The \(i\)th and \(j\)th choices are (weakly) complementary if for all \(x\),

\[
f(1,1,x_{-ij}) - f(0,0,x_{-ij}) \geq \left( f(1,0,x_{-ij}) - f(0,0,x_{-ij}) \right) + \left( f(0,1,x_{-ij}) - f(0,0,x_{-ij}) \right)
\]

To treat groups of coordinated changes, it is helpful to introduce some notation. Given profiles of decisions \(x,y \in \{0,1\}^n\), let \(x \lor y\) be the profile that specifies the union of the changes in \(x\) and \(y\). Mathematically, \(x \lor y\) is the component-wise maximum of \(x\) and \(y\). Similarly, let \(x \land y\) be the profile that specifies the intersection of the changes in \(x\) and \(y\). Mathematically, \(x \land y\) is the component-wise minimum of \(x\) and \(y\).
Using the just-defined notation, complementarity entails two mathematical conditions on the decision maker’s optimization problem. The first condition restricts the constraint set: whenever \( x \) and \( y \) are both feasible decision profiles, then so are \( x \lor y \) and \( x \land y \). If \( x \lor y \) were not included, that would mean that implementing some changes could preclude other changes, blocking the tendency for the changed practices to appear together. If \( x \land y \) were not included, that would mean that failing to implement some changes could require implementing others, blocking the tendency for the unchanged practices to appear together. A set that satisfies this first restriction is a sublattice and is defined formally as follow:

**Definition.** A set \( S \subseteq \mathbb{R}^n \) is a sublattice if \( \forall x, y (x, y \in S) \Rightarrow (x \lor y, x \land y \in S) \).

The second condition is a payoff property similar to that identified by (1). The property can be written as \( f(x \lor y) - f(x \land y) \geq f(x) - f(x \land y) + f(y) - f(x \land y) \). This inequality asserts that starting from a point where all the practices described by \( x \land y \) are sure to be implemented, the additional return to implementing all the remaining practices, which is \( f(x \lor y) - f(x \land y) \), is at least as great as the sum of the returns from implementing each separately. A function with this property is said to be supermodular. For the definition, we rewrite this inequality in a more symmetrical form.

**Definition.** A function \( f : S \rightarrow \mathbb{R} \) is supermodular if

\[
(\forall x, y \in S) f(x \lor y) + f(x \land y) \geq f(x) + f(y).
\]

The decision problems we will be evaluating are ones in which there may be some separate costs of returns \( C_i(x_i) \) associated with each decision, but all of the payoff interactions are described by the function \( f \). We impose no restrictions on the cost
functions except that each takes a single argument: $C_i : \mathbb{R} \to \mathbb{R}$ . This leads us to the following formulation:

**Definition.** The decision problem

$$\max_{x \in S} f(x) - \sum_{i=1}^n C_i(x_i)$$

has **complementarities** if $S$ is a sublattice and $f$ is supermodular.

### 2.1 Example: Producer Theory

One example to illustrate complementarity arises in the neoclassical theory of a competitive firm. With two inputs and a Cobb-Douglas production function, the firm solves the problem: $\max_{x \in \mathbb{R}^2_+} \lambda x_1^\alpha x_2^\beta - w \cdot x$ , where $\lambda > 0$ . We may check the two complementarity conditions for this problem. First, the constraint set $S = \mathbb{R}^2_+$ is a sublattice because for any $x, y \in \mathbb{R}^2_+$ and for $i = 1, 2$ , $(x \land y)_i = \min(x_i, y_i) \geq 0$ and $(x \lor y)_i = \max(x_i, y_i) \geq 0$ , so $x \lor y, x \land y \in \mathbb{R}^2_+$ . Also, the incremental return to any increase from, say, $x_1$ to $\hat{x}_1 > x_1$ is $\lambda (\hat{x}_1^\alpha - x_1^\alpha)x_2^\beta - w_1(\hat{x}_1 - x_1)$ , which is increasing in $x_2$ if $\alpha, \beta > 0$ . With continuous choice variables, a convenient way to make the same point is to observe that the marginal return to $x_1$ , $\lambda \alpha x_1^{\alpha-1}x_2^\beta - w_1$ , is increasing in $x_2$ .

### 2.2 Theorems about Decision Problems with Complementarities

The core of the theory comprises ten mathematical statements about decision problems with complementarities. The list below reports theorems that depend only on the complementarity conditions—sublattices and supermodularity—and not on any other common economic structure, such as divisibility (commonly assumed to justify the use of
first-order conditions) or convexity (commonly assumed to imply the existence of supporting prices). These theorems are about decision problems with complementarities and their scope is not limited, for example, to problems in price theory.

### 2.2.1 Complementarity is a Pairwise Relationship

Theorems 1a and 1b explain the claim in the introduction that complementarity is, essentially, a pairwise relationship among decisions. Theorem 1a is about sublattices. It asserts that a subset of \( \mathbb{R}^n \) is a sublattice exactly when it can be expressed as the conjunction a set of sublattice restrictions for each pair of decision variables separately. Theorem 1b concerns supermodularity. It asserts that a function on a product set (such as \( \mathbb{R}^n \)) is supermodular exactly when it is supermodular in each pair of variables separately.

**Theorem 1a** (Topkis, 1976). The set \( S \subseteq \mathbb{R}^n \) is a sublattice if and only for each \( 1 \leq i < j \leq n \), there exist a sublattice \( S_{ij} \subseteq \mathbb{R}^2 \) such that \( S = \bigcap_{i,j=1,j<i}^n \{ x \mid (x_j, x_j) \in S_{ij} \} \).

**Theorem 1b** (Topkis, 1978). Suppose that \( f : S \to \mathbb{R} \), where \( S \) is a product set: \( S = \times_{i=1}^n S_i \), where each \( S_i \subseteq \mathbb{R} \). Then \( f \) is supermodular if and only if for all \( 1 \leq i < j \leq n \) and all \( x \in S \), the function \( g(z_i, z_j) \equiv f(z_i, z_j, x_{-ij}) \) is supermodular.

### 2.2.2 The Set of Optimizers is a Sublattice

Theorem 2 is about the structure of the set of optimizers in a decision problem with complementarities, claiming that it is a sublattice. In practice, this means that in searching for an optimum, if we find an optimal profile at which certain changes are made, then there is also an optimal profile at which all of those changes are made. Symmetrically, if there is an optimal decision profile in which certain changes are not
made, then there is an optimal profile in which none of those changes are made. At least weakly, at an optimum, the individual decisions cluster: they are adopted together or not at all.

**Theorem 2** (Topkis, 1978). Suppose that (2) is a decision problem with complementarities. Then the set of optimal solutions \( \arg \max_{x \in \mathcal{S}} f(x) + \sum_{i=1}^{n} C_i(x_i) \) is a sublattice.

### 2.2.3 “Coherent” Searches Can Find and Verify the Optimum

The message of theorem 2 is further reinforced by considering how to locate and verify an optimum. Suppose that, in a decision problem with complementarities, we start our search for an optimum at some point \( z \). Since \( z \) is arbitrary, the optimum might be in any direction, perhaps at some point with higher values of some components and lower values of others. Since we have made no convexity assumptions, even if \( z \) is optimal in some local neighborhood, it may still fail to be a global optimum. At noted by Levinthal (1997) and Rivkin (2000), it can be particular difficult if the landscape is “rugged”, with numerous local optima, and the general problem may even be intractable in the sense of NP-completeness. Is there some way to restrict the search?

If the decision problem has complementarities, then two important statements can be made. First, more than half of the gain to moving from decision profile \( z \) to the optimum can be gotten just by optimizing over the sets with coherent changes, that is, with all choices weakly increased or all weakly reduced. Second, as a corollary, if there are no gains to be had in those coherent directions, then \( z \) is actually an optimal choice. To make these statements precise, we define \( x \succeq y \) to mean \( x_i \geq y_i \) for \( i = 1, \ldots, n \).
Theorem 3. (Milgrom and Roberts, 1995). Suppose that (2) is a decision problem with complementarities. Then

\[
\left( \max_{x \in S : z \geq x \cup x \leq z} f(x) - \sum_{i=1}^{n} C_i(x_i) \right) - \left( f(z) - \sum_{i=1}^{n} C_i(z_i) \right)
\geq \frac{1}{2} \max_{x \in S} \left( f(x) - \sum_{i=1}^{n} C_i(x_i) \right) - \left( f(z) - \sum_{i=1}^{n} C_i(z_i) \right).
\]

Corollary 3. Suppose that (2) is a decision problem with complementarities. Then

\[
z \in \arg \max_{x \in S} f(x) + \sum_{i=1}^{n} C_i(x_i) \text{ if and only if } z \in \arg \max_{x \in S \text{ and } (z \geq x \text{ or } x \leq z)} f(x) + \sum_{i=1}^{n} C_i(x_i).
\]

Thus, an understanding of complementarities may simplify the process of finding an optimum.

2.2.4 Comparative Statics are Like Those of Demand Theory

The fourth theorem is about comparative statics, that is, about how the solution changes when a parameter changes. To motivate the discussion, suppose there is an exogenous change affecting just one of the variables, such as a price change that makes increasing \( x_1 \) more profitable. If that change is enough to change the optimal decision, then the complementarity of choices would tend to favor the other choices as well, leading to increased levels of those decisions, too. Indeed, this is the very definition of complementarity in demand theory: reducing the price of an input raises the demand for complementary inputs. So, a comparative statics theorem of this sort is both useful for applications and verifies that the new definition of complements is consistent with earlier uses in demand theory.

For our formulation, however, we do not limit attention to prices, at least as narrowly defined, since many of the relevant decisions are not input quantities. Instead,
we want to consider a broader range of parameter changes that might favor making some of the relevant changes. In the spirit of demand theory, we model the parameter like a price as $\theta \in \mathbb{R}$ and rewrite the choice problem with $x \in \mathbb{R}^n$, and $S \subseteq \mathbb{R}^{n+1}$ as follows:

$$X(\theta) = \arg \max_{\{x(x, \theta) \in S\}} f(x, \theta) - \sum_{i=1}^n C_i(x_i) \quad (3)$$

Here, $X(\theta)$ is the set of optimizers, which we will discuss as if it were a singleton. Formally, the theorem below applies even when the set has multiple elements or is empty, with no elements. The parameter $\theta$ in (3) enables us to capture changes in the constraint set or in the objective.

If we limit attention to parameters for which $X(\theta)$ is a singleton, it is clear what it means for the optimal solution to be non-decreasing in $\theta$, but we cannot guarantee in general that the optimal solution will be unique. To treat the general case, we need a word and a definition that coincides with non-decreasing for the well understood case but also describes a useful corresponding concept for the general case. The word is “isotone” and the definition is the following one.

**Definition.** The set-valued function $X(\bullet)$ is isotone if for all $\theta > \theta'$, if $x \in X(\theta)$ and $x' \in X(\theta')$, then $x \vee x' \in X(\theta)$ and $x \wedge x' \in X(\theta')$.

**Theorem 4** (Topkis, 1978). In problem (3), suppose that $S$ is a sublattice and $f$ is supermodular. Then $X(\bullet)$ is isotone.

If we limit attention to parameters for which $X(\theta)$ is a singleton, then the theorem asserts that, on that domain, all of the components of the decision profile are non-decreasing functions of $\theta$. So, this theorem says that the new notion of complementarity
coincides with the demand theory notion in such cases. Moreover, if we think of \( \theta \) as a random variable and assume that \( X(\theta) \) is almost always a singleton, then if what is observed are optimal choices, the choices will be positively correlated. This happens because they are all non-decreasing functions of the same one-dimensional random variable.

2.2.5 Complementarity Conditions are Necessary for Some Comparative Statics

The comparative statics implications of complementarity are interesting, but one might wonder whether similar results can be derived from alternative conditions. They cannot. Both the sublattice condition and the supermodularity condition are essential. We assert this with two theorems, with treat the two conditions separately. We limit attention to finite feasible sets to avoid certain technical complications.

**Theorem 5a** (Milgrom and Shannon, 1994). Suppose that the constraint set \( S \) is finite but is not a sublattice. Then, for some cost functions \( C_i, i=1,\ldots,n \), and some \( j \in \{1,\ldots,n\} \), the function \( X(\theta) = \arg \max_{\{x: x \in S\}} f(x) - \sum_{i=1}^{n} C_i(x) + \theta x_j \) is not isotone.

**Theorem 5b** (Milgrom and Shannon, 1994). Suppose that constraint set \( S \) is \( \{0,1\}^n \) and the function \( f \) is not supermodular. Then, for some cost functions \( C_i, i=1,\ldots,n \), and some \( j \in \{1,\ldots,n\} \), the function \( X(\theta) = \arg \max_{x \in S} f(x) - \sum_{i=1}^{n} C_i(x) + \theta x_j \) is not isotone.
2.2.6 …but Limited Results Extend to Some Related Systems

Sometimes, we study decision problems that can be broken into modules, where decisions about the modules, denoted by $x$, are complementary, but a set of more specialized decisions within each module has a more complicated structure. To study such cases, let $y_i$ denote the decisions “within” module $i$, which make interact with $x_i$ or with other decisions within the module, but not with decisions in any of the other modules. Formally, the optimization problem is:

$$X(\theta), Y(\theta) = \arg \max_{(x, \theta) \in S, y_1 \in Y_1, \ldots, y_n \in Y_n} f(x, \theta) - \sum_{i=1}^{n} C_i(x_i, y_i)$$

(4)

**Theorem 6.** In problem (4), suppose that $S$ is a sublattice and $f$ is supermodular. Then $X(\bullet)$ is isotone.

The theorem asserts that we can still make assertions about the complementary variables, even if their interaction with other related variables outside the cluster is arbitrarily complicated. The important condition for this conclusion is that these “other” variables do not interact with variables outside their own modules.

2.2.7 Long-Run Changes are Larger than Short-Run Changes

Another important idea that we borrow from demand theory is that, in certain circumstances, long run adaptations are larger in magnitude than short-run adaptations. As is standard in economics, the short run refers to a period over which some decisions are fixed while the long-run refers to a period over which all decisions can change. Let $x$ denote the group of decisions that are free in the short run and $y$ the decisions that are free only in the long run.
For simplicity of our statement, we limit attention to values of the parameter for which the optimal long- and short-run decisions are unique. Thus, let \( x(\theta, y) \) denote the short-run optimum for any given values of the parameter and the long-run decision \( y \):

\[
x^*(\theta, y) \in \arg \max_{(x,y,\theta) \in S} f(x, y, \theta) - \sum_{i=1}^{n} C_i(x_i) - \sum_{j=1}^{m} K_j(y_j)
\]

(5)

We use \( y(\theta) \) to denote the long-run optimal value of \( y \) for any fixed value of the parameter \( \theta \).

\[
y^*(\theta) \in \arg \max_y \left( f(x^*(\theta, y), y, \theta) - \sum_{i=1}^{n} C_i(x^*(\theta, y_i)) - \sum_{j=1}^{m} K_j(y_j) \right)
\]

(6)

Notice that the long-run optimal value of \( x \) is just \( x^*(\theta, y^*(\theta)) \).

When the parameter changes, say by increasing from \( \theta' \) to \( \theta \), the short-run reaction is for \( x \) to increase in response to the parameter change. In the long-run, \( y \) also increases, and that acts like a parameter change to lead to a further increase in \( x \). So, \( x \) changes more in the long run than in the short run. A symmetric argument applies when the parameter change is a decrease. These relations are summarized by the following theorem.

**Theorem 7.** (Milgrom and Roberts, 1996). If \( S \) is a sublattice and \( f \) is supermodular, then \( x^* \) and \( y^* \) are both non-decreasing. In particular, if \( \theta > \theta' \), then

\[
x^*(\theta, y^*(\theta)) \geq x^*(\theta', y^*(\theta)) \geq x^*(\theta', y^*(\theta')) \quad \text{and} \quad x^*(\theta, y^*(\theta)) \geq x^*(\theta, y^*(\theta')) \geq x^*(\theta', y^*(\theta')) .
\]


2.2.8 Dynamical Systems of Complements Exhibit Momentum

A related conclusion applies not merely to long- and short-run equilibrium changes, but also to explicitly dynamical systems in which frictions may limit the rate of adjustment. The system starts in a state \( x_0 \) and moves, by optimization, through a series of states \( x_1, x_2 \) and so on. The states may, for example, include levels of assets and associated employment, where a too rapid adjustments of assets is impossible or costly. For example, building a structure in half the usual time typically entails significant additional costs, while attempting to complete a large software project in half the time may be impossible at any price. The conclusion is that there is momentum in a system of complementary choices: once the system variables begins moving in a given direction (up or down), they will tend to continue in that direction.

The assumption that adjustments are impossible or costly are quite naturally modeled by the idea that that are restrictions on successive choices, that is, \((x_{t-1}, x_t) \in S\) and that today’s payoffs depend on choices from yesterday as well as today: \( f(x_{t-1}, x_t) \). We study both myopic and far-sighted optimizations, as represented by the two problems below:

\[
\max_{(x_{t-1}, x_t) \in S} f(x_{t-1}, x_t) - C(x_t) \tag{7}
\]

\[
\max_x \sum_{t=1}^{\infty} \delta^t \left( f(x_{t-1}, x_t) - C(x_t) \right) \text{ subject to } (x_{t-1}, x_t) \in S \text{ for all } t \geq 1. \tag{8}
\]

**Theorem 8** (Milgrom, Qian and Roberts, 1991). If \( S \) is a sublattice and \( f \) is supermodular, then for both problems (7) and (8), if \( x_t^* \geq x_0^* \), then for all \( t \geq 1 \), \( x_t^* \geq x_{t-1}^* \).
2.2.9 Complementarities Create a Value to Simple Coordination

Finally, we look at the implications of complementarities for coordination. Any decision system can entail errors, but in a system of complements it is especially important that any errors be coherent, that is, coordinated. Going too far in some direction is less costly if the other choices are exaggerated in the same direction.

**Theorem 9.** Let \( \varepsilon_1, \ldots, \varepsilon_n \) be independent, identically distributed random variables. If \( f \) is supermodular, then, for every \( x \) and every vector \( \alpha \in \mathbb{R}_+^n \),

\[
E \left[ f(x_1 + \alpha_1 \varepsilon_1, \ldots, x_n + \alpha_n \varepsilon_n) \right] \leq E \left[ f(x_1 + \alpha_1 \varepsilon_1, \ldots, x_n + \alpha_n \varepsilon_1) \right].
\] (9)

The point of theorem 9 is that, regardless of the starting point \( x \), if there are to be random errors in all of the choices, then regardless of their magnitudes (which is governed by \( \alpha \)), it is better that all the errors are perfectly correlated rather than being independent. In a system with complementarities, even if choices cannot be optimized, coordination remains important. Thus, having a single, decisive leader in an organization may be better than distributing decision-rights even if the central decision-maker is imperfectly informed.

2.2.10 Returns to Scale/Scope can Create Complementarities

One of the most common ways for complementarities to arise is from increasing returns to scale. A simple example is the function \( f(x_1, x_2) = g(x_1 + x_2) \). It is easy to check that if \( g \) is convex, then \( f \) is supermodular. Indeed, the marginal return to \( x_1 \) is \( f_1(x_1, x_2) = g'(x_1 + x_2) \), which is non-decreasing in \( x_2 \) if and only if \( g \) is convex.
A related example comes from the use of shared inputs for which there are economies of scale. For example, suppose that research that reduces the costs of chip manufacturing can be used both for memory chips and for microprocessors. Let $k$ denote the expenditures on knowledge—research—and suppose the costs of production for goods $i = 1, 2$ are $c_i(x_i, k)$, where $\partial c_i / \partial x_i$ is decreasing in $k$. Then, the firm’s total profit is

$$f(x_1, x_2, k) = R_1(x_1) + R_2(x_2) - c_1(x_1, k) - c_2(x_2, k) - k$$

is supermodular, regardless of the revenue functions $R_i(x_i)$. The shared input, which reduces the marginal cost of both kinds of manufacturing, makes the two complements.

Formally, this analysis relied on explicitly including the choice variable $k$ in the formulation. If it is convenient, $k$ can be legitimately pushed into the background by applying the following result.

**Theorem 10** (Topkis, 1978). Suppose that $f(x, k): \mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}$ is supermodular and $S \subseteq \mathbb{R}^n \times \mathbb{R}^m$ is a sublattice. Then, the function

$$g(x) = \max_{\{k : (x, k) \in S\}} f(x, k)$$

is supermodular and the set $S_x = \{x \mid \exists k (x, k) \in S\}$ is a sublattice.

The theorem tells us that if the original decision problem exhibits complementarity and if some of the variables $k$ are optimized away to allow us to focus just on the variables $x$, then the decision problem for these remaining variables also exhibits complementarity.
3 Empirical Evidence

Much of the first evidence on the relevance of organizational complementarities has come from case studies of individual firms. Cases often provide the richest insight into the nature of complementarities and can be very powerful for shaping our intuition about the underlying mechanisms at work. Conclusions drawn from case studies, however, can be misleading because the observer may identify relationships that are idiosyncratic and not generalizable. To address these failings, econometric techniques have increasingly been used over the past decade to test theories of complementarities using sets of firms or establishments, rather than just a single case. Recently, some economists have argued that international differences in business practices and performance can be traced back to complementarities in organizations. In this section, we review this literature with a more formal discussion of empirical techniques in the following section.

3.1 Case Studies

A 1975 Harvard Business School case detailing Lincoln Electric’s unique business methods and compensation scheme is among the School’s best-selling cases ever, and is still widely taught today. Lincoln Electric, an arc-welding company that began operations in 1895, had not laid off a worker in the United States since 1948\(^5\), and had average earnings for hourly workers that are double those of their closest competitors

\(^4\) Inevitably, our review will be incomplete. Ennen and Richter conducted a computerized search of the literature and found that between 1988 and 2008, 1398 papers in management, economics, marketing, R&D and information systems journals contain the word stem “complement”. They go on to review 73 of these, an overlapping set with the papers discussed below. See also a useful discussions by Ichniowki and Shaw (2003) and Porter and Sigglekow (2008).

(Milgrom and Roberts 1995, p.200). The company uses piece rates as its main form of compensation, where workers are paid by the amount of output they produce, rather than a fixed salary. Once the piece rates are set, the company commits to that rate forever, unless new machinery or production methods are introduced. In addition, the company pays individual annual performance bonuses based on its profits that typically amount to 60-90% to the regular annual earnings for an average employee. An interesting question is: If the company’s methods are so widely studied, why has the remarkable success of Lincoln Electric not been copied by other firms? Rather than looking for the answer in the piece rates alone, Milgrom and Roberts (1995) hypothesize that it is the complementarities inherent in the workplace that make Lincoln Electric so difficult to copy. To copy piece rates may be easy enough, but all of the other distinctive features of the company, such as internal ownership, promoting from within, high bonuses, flexible work rules, and credible commitments are part of a reinforcing system. A system is much more difficult to reproduce than just one or two parts, especially when one considers that many of the important complements, like corporate culture, may be difficult to accurately observe and even harder to translate to other contexts.

More recently, longitudinal case studies by Nicolaj Siggelkow (2001, 2002a, 2002b) have found that complementarities can explain the evolution of the Liz Claiborne cosmetics company and Vanguard Group in financial services. For instance, Siggelkow found that complementarities at Liz Claiborne can limit managers’ options when responding to environmental changes. This leads them to favor “fit-conserving” change even when it decreases the appropriateness of the overall choice set.
Holmes (2001) develops a model of complementarities relating to the use of technology in the retail sector in an attempt to explain the emergence of big-box retailers. The author explores the complementarities between the use of bar codes and computer tracking of inventory. His model shows that “new technology induces stores to increase delivery frequency.” (p.708) This leads to his second finding, that with more frequent deliveries, it is more efficient for stores to be larger. He points out that if the store remained the same size but received twice as many deliveries as before, then the trucks would only be half as full for each delivery (p.708).

Barley (1986) explores the introduction of identical CT scanners in two different hospitals in the same metropolitan area and finds that identical technology led to very different organizational outcomes depending on what other practices were also in place. The CT scanners disrupted the existing power structure between the radiologists and technicians, and led to different forms of organization around the technology. He concludes that

“Technologies do influence organizational structures in orderly ways, but their influence depends on the specific historical process in which they are embedded. To predict a technology’s ramifications for an organization’s structure therefore requires a methodology and a conception of technical change open to the construction of grounded, population-specific theories.” (p.107)

Autor, Levy and Murnane (2002) study the effect of introducing check imaging and optical character recognition (OCR) technologies on the reorganization of two floors of a bank branch. In the downstairs deposit-processing department, image processing led to computers substituting for high school educated labor. In the upstairs exceptions-processing department, image processing led to the integration of tasks, with “fewer
people doing more work in more interesting jobs.” (p.442). The authors conclude that the same technology can have radically different effects on workplace reorganization, depending on the level of human capital and other non-technology related factors, even within one building of a single company.

In some cases, the complementarities among practices are subtle and not even well understood by the participants themselves. Brynjolfsson, Renshaw and Van Alstyne (1997) write about the business process reengineering efforts at one of Johnson and Johnson’s manufacturing plants. The company sought to make almost exactly the sort of transition that Milgrom and Roberts (1990) describe from traditional manufacturing practices, similar to those used by Ford Motor Company in the early years the 20th century, to “modern manufacturing.” Despite a clear plan and an explicit written description by senior management of many of the specific complementarities inherent in both the old and the new systems, the initial reengineering efforts were unsuccessful. After spending millions of dollars on new, highly flexible production equipment, key performance metrics were largely unchanged. An interview with a 30-year veteran line supervisor revealed a potential explanation. He was sincerely intent on making the transition a success and he explained “I’ve been here a long time and I know that the key to productivity is avoiding change-overs [the transition from one product to another using the same equipment]. You get killed in the change-overs.” Accordingly, he and his team

---

6 Milgrom and Roberts (1990) trace a broad set of organizational practices to improvements in information technology. One extended example they explore involves the use of CAD/CAM engineering software in manufacturing. This software promotes the use of programmable manufacturing equipment, which in turn makes it possible to offer a broader product line and more frequent production runs. This in turn affects marketing and organization. Shorter production runs lower inventory costs, which lower prices. Buyers also value shorter delivery times. This means that the firm now has a substantial incentive to reduce other forms of production delays and invest in computerized ordering systems. The example illustrates how important it is to think in terms of systems of activities, rather than trying to adopt one particular practice.

7 See Appendix B for an example of reengineering efforts at Merrill Lynch.
were using the new flexible production equipment to produce long, unchanging product runs. This is precisely the opposite of what management had intended and what Milgrom and Roberts predicted in their 1990 paper (p. 524). However, the supervisor and his team had built up numerous heuristics like this as part of their decades-old investment in work practices. In other words, their organizational capital, much of it implicit, turned out to be a poor fit for the new physical capital. Ultimately, the company cancelled the change effort at the existing site and re-started it at a new site, with a hand-picked set of new, mostly very young, workers. The new effort was such a success that the windows were painted black to make it more difficult for competitors to learn about the new system of technology and practices.

This kind of difficulty in managing transitions appears to be common. For instance, McAfee (2002) quantitatively examines an ERP (Enterprise Resource Planning) system implementation over a period of several months in one firm. The ERP system was introduced without any other business process changes at first. McAfee finds a significant dip in company performance after it adopted the system, which he attributed to this lack of business process redesign. After several months, however, the firm adapted, and post-ERP performance was better than pre-ERP adoption, reflecting the successful adjustment of complementarity practices.

In many other cases, change efforts remain unsuccessful when the complementarity organizational practices are not revised along with the introduction of new technologies. For instance, General Motors (GM) spent $650 million on new technology at one plant in the 1980s but did not make any important changes to its labor
practices. The new technology at GM did not result in any significant quality or productivity improvements (Osterman 1991).

### 3.2 Econometric Studies of Complementarities

#### 3.2.1 United States

One of the clearest analyses of complementarities and productivity comes from Ichniowski, Shaw and Prennushi (1997). They use data from 36 steel finishing lines in 17 different companies, and measure the impact of different clusters of workplace practices on productivity and product quality. By focusing on a single production process, they are able to use a narrow productivity metric (uptime of the production line) and avoid many potential sources of unobserved heterogeneity. One important difference that remained was the choice of work practices adopted at the line, which varied across lines, as well as across time at the same line in about 14% of the cases. They looked at both correlations as well as productivity regressions and found evidence that work practices that include incentive pay, teams, flexible job assignments, employment security and training were mutually complementary, as compared to a more traditional set of work practices. Their two key conclusions are that 1) workplace practices tend to cluster more than random chance would predict, and b) clusters of workplace practices have significant and positive effects on productivity, while isolated changes in individual work practices have little effect on productivity.

Bresnahan, Brynjolfsson and Hitt (2002) run an analysis at the firm level and reach similar conclusions. The authors examine 300 large firms using data from 1987-
1994 from both manufacturing and service industries in the United States. They study the organizational complements to technology and their impacts on productivity, and find that “increased use of IT, changes in organizational practices, and changes in products and services taken together are the skill-biased technical change that calls for a higher skilled-labor mix” (p. 341). Furthermore, the interaction of IT, workplace organization, and human capital are good predictors of productivity. Because organizational changes take time, this can help explain the finding that the largest productivity increases often come several years after major IT investments (Brynjolfsson and Hitt 2003).

Using plant-level data on almost 800 establishments from 1993-1996, Black and Lynch (2004) find that productivity is positively correlated with the proportion of non-managers using computers, teams, profit sharing, employee voice, and reengineering. They assert that “workplace organization, including re-engineering, teams, incentive pay and employee voice, have been a significant component of the turnaround in productivity growth in the US during the 1990s” (p. F97). In a related 2001 paper, Black and Lynch examine the impact of a Total Quality Management (TQM) system on productivity. Using data from 600 manufacturing plants from 1987-1993, they find that adopting a TQM system alone does not meaningfully impact productivity. However, they do find that giving employees greater voice or profit-sharing programs alongside a TQM program has significantly positive effects on productivity.

8 Using data of about 500 large firms from 1987-1994, Brynjolfsson and Hitt (2003) find that the returns to IT are no different than those of ordinary capital when looking only at the short-term, one-year impact. However, when they look at 5- or 7-year time horizons, the productivity and output contributions of the same technology investments are five times as large. For a broader review of related findings see Brynjolfsson and Hitt (2002).
Autor, Levy and Murnane (2003) conduct a study the impact of computerization on job tasks. They use job and occupation data from the U.S. Department of Labor’s Dictionary of Occupational Titles from 1960 to 1998. In line with the other studies we examined, the authors derive two main conclusions. First, computers substitute for routine tasks, and second, that computers complement workers doing complex or problem-solving tasks.

More recently, Garicano and Heaton (2010) find support for complementarities in a public sector context. They use information from a panel of police departments in the U.S. that contains detailed information on IT usage and organizational practices between 1989 and 2003. The productivity variables in this context are local crime clearance rates and crime rates, controlling for local demographics. They find that IT by itself has little positive impact on either on those performance metrics- that is departments which invested more in IT did not see larger drops in crime or better arrest rates. However, when IT was introduced together with a new system of organizational practices, IT had significant effects on police performance. The successful system of practices in this context is the “Compstat” system, which combines real-time geographic information on crime with strong accountability by middle managers in the form of daily group meetings, geographic resource allocation, and data-intensive police techniques. The Compstat practices were associated with crime clearance rates on average of 2.2 percentage points higher in agencies implementing this integrated set of practices while the individual practices composing Compstat had no independent ameliorative impact on crime levels or clearance rates.
Complementarities have also been explored in the strategy literature, often as part of the resource-based view of the firm. For instance, Tanriverdi and Venkatraman (2005) analyze 303 multibusiness firms and find evidence of complementarities in the performance benefits of combining customer knowledge, product knowledge and managerial knowledge are present in combination. In contrast, both market-based and accounting-based performance metrics are not significantly improved from any of these types of knowledge in isolation.

Researchers in the R&D literature have identified complementarities in inter-firm relationships. For instance, Belderbos, Carree and Lokshin (2006) found evidence of complementarity relationships when measuring the productivity effects of R&D cooperation strategies among competitors, customers and universities. Similarly, Colombo, Grilli and Piva (2006) found that complementarity assets, including technologies and commercial assets, could explain the success of alliances for high-tech start-ups.

3.2.2 International Comparisons

There has been much debate about why productivity growth has been higher in the United States than in Europe (see O’Mahony and Van Ark 2003 for a review of the literature surrounding this issue). One class of possible explanations focus on various country specific factors that are external to the organization of the firm, such as taxes, regulation, and culture. However, another promising line of research has focused on the differences in the ways that firms organize themselves from country to country.
Recent research suggests that differences in productivity between the United Kingdom and the United States may indeed be due to organizational differences and, more specifically, to the firm-specific IT-related intangible assets that are often excluded in macroeconomic growth accounting exercises. The research compares differences between U.S. and U.K. owned firms operating in the United Kingdom. With this data, the authors hope to discover whether there is something unique about American ownership versus being located on U.S. soil (with less regulation or stronger product market competition) that drives higher productivity growth.

Bloom, Sadun and Van Reenen (2007) conduct a study on a panel of about 8,000 establishments across all industries in the United Kingdom from 1995-2003. They found that U.S.-owned establishments were both more IT-intensive and more productive than British or other foreign-owned companies operating in the United Kingdom. They specifically attribute this difference to complementarities between IT and the types of organizational capital that are more common in American firms.

Crespi, Criscuolo and Haskel (2006) present similar evidence that American firms operating in the United Kingdom are more productive and implement more related organizational capital than do their U.K. counterparts. Their study, based on a data set of approximately 6,000 British firms from 1998-2000 across all industries, introduce a variable as a proxy for organizational capital. The authors find that IT has high returns regardless of organizational factors. However, when they control for an organizational proxy variable, the measured returns attributed to IT are lower, which suggest that some of the measured IT-related boost in productivity actually came from organizational factors. In contrast to the evidence of complementarity between IT and organization, the
authors find that there is “no additional impact on productivity growth from the interaction of organizational capital and non-IT investment.” The authors’ new findings are that organizational change is affected by ownership and market competition, and that U.S. owned firms operating in the United Kingdom are more likely to introduce organizational change than non-U.S. owned firms, who are more likely to introduce organizational change than domestically owned (U.K.) firms.

Bugamelli and Pagano (2004) work with a dataset of about 1,700 Italian manufacturing firms and conclude that Italian firms have a seven-year technological gap compared to similar American firms. They reject the notion that the gap is due to sectoral specialization of the Italian economy into industries such as textiles, clothing, and food, which are not as IT intensive. Rather, they argue that it is the missing complementary business re-organization which has been the barrier to investment in IT in Italy.

Caroli and Van Reenen (2001) generate three major findings with British and French establishment data from 1984 and 1990 (Great Britain) and 1992 (France). One is that organizational change is associated with a decline in demand for unskilled workers. Second, higher cost of skills leads to a lower probability of organizational change. Third, organizational changes are associated with greater productivity in establishments with more skilled workers. All three findings are consistent with complementarities between workplace reorganization and skilled labor.
4 Testing for Complementarities: Theory and Practice

When the costs and benefits of organizational practices can be accurately measured, complementarities theory provides clear empirical predictions. In this section, we consider two types of statistical tests for complementarities: performance differences and correlations. For each test, we discuss the assumptions that are necessary to make them effective ways to reveal the existence and magnitude of complementarities. In many cases, the conditions that make it difficult to identify complementarities by examining performance differences will actually make it more likely that they can be identified via correlations, and vice versa. We then analyze the role of unobserved heterogeneity in the costs or benefits of changing organizational practices. This can bias tests for complementarities. Finally, we discuss various empirical approaches for overcoming these problems.

4.1 Performance Equations

Consider a case where potential complements $y_1$ and $y_2$ each vary independently and exogenously. For instance, a new computer system, $y_1$, is implemented randomly across offices based on a lottery, while employee training, $y_2$, is deployed randomly across employees based on the last digits of their social security number. Each choice is binary, so $(y_1, y_2) \in \{0,1\}^2$. Thus, given the independence of the design choice, we will have a random sample in each of the four quadrants. If the practices are complements, then by equation (1), the change in total output is greater when both practices are
implemented together than the sum of the changes when each practice is implemented separately:

\[ f(1,1) - f(0,0) \geq f(1,0) - f(0,0) + f(0,1) - f(0,0) \]

This suggests an obvious test statistic for complementarities using performance differences:

\[ \kappa_p = f(1,1) + f(0,0) - f(1,0) - f(0,1) \]  \hspace{1cm} (10)

Of course, \( f \) may be measured with error and other exogenous factors may affect performance, either directly or in combination with one of the complements. Thus, a typical approach is to estimate performance with a multivariate regression, which accounts for these other factors and their interactions, holding them fixed, thereby allowing the researcher to focus on the potential complementary practices themselves. When \( \kappa_p \) is significantly greater than zero, we can reject the null hypothesis of no complementarities.

Many authors have implemented this approach. For instance, as noted in the previous section, Ichniowski, Shaw and Prennushi (1997) compared steel finishing lines and, using ordinary least squares and fixed effects regressions, found that those which implemented certain human resources practices together were significantly more productive than those that implemented the same practices separately. More recently, Bloom, Garicano, Sadun and Van Reenen (2008) gathered data on information technology and organizational practices for a sample of American and European firms. In each case, the predicted pattern of complementarities was evident.

\[ ^9 \text{To simplify notation, we omit reference to other choices of the decision-maker } x_{ij} \text{ or exogenous variables.} \]
Of course, in many cases the variables will naturally be continuous, such as the quantity of IT capital stock or hours spent on training, so information would be lost if they are discretized into two categories. Instead, the continuous versions of the variables can be included in a performance regression along with an interaction term that multiplies two of the choice variables together. If the variables are normalized with the means set equal to zero, then it is easy to interpret the coefficient of the interaction term under the assumption that the choices where made independently and exogenously. A value greater than zero at a chosen significance level (such as 5%) is evidence of complementarity.

Brynjolfsson, Hitt and Yang (2002) provide a plot that shows market value as a continuous function of both IT and an index of organizational practices, ORG.

Figure 1: Normalized market value, ln(mv) as a function of IT investment ln(i) and an index of organizational practices, org at a sample of 372 firms (From Brynjolfsson, Hitt and Yang, 2002).
The performance tests can be generalized to the case of three or more complements. For instance, Aral, Brynjolfsson and Wu (2011) and Tambe, Hitt and Brynjolfsson (2012) each model different three-way systems of complements. The theory suggests four performance tests of complementarities, which can readily be seen via a cube diagram. For instance, Tambe, Hitt and Brynjolfsson test for complementarities in the triple \((x, y, z)\) where \(x\): IT investments, \(y\): decentralized work organization and \(z\): external orientation. There are eight potential systems, and the theory of complementarities predicts that they will be related to each other by the four inequalities described in the diagram.\(^{10}\)

\(^{10}\) Additional inequalities may be inferred comparing various the performance of intermediate systems with the performance of the two fully complementary systems at \((0,0,0)\) and \((1,1,1)\).
4.2 Correlations and Demand Equations

The assumption that the adoption decisions are exogenous and uncorrelated is a strong one. In particular, in most cases managers will be consciously trying to maximize, or at least increase performance, so when two practices are actually complementary, managers will seek to adopt them together. If the managers have perfect foresight and full control over both of the choice variables, then in the absence of other exogenous forces, the complementary variables will always be adopted together. In this case, all the
observations \((y_1, y_2)\) will be either \((0,0)\) or \((1,1)\); there will be no “off-diagonal observations in the data. As a result, it will be impossible to identify values for \(f(1,0)\) or \(f(0,1)\), and we cannot estimate \(\kappa_p\) econometrically.

Similarly, market competition might reduce or eliminate the population of firms which attempt to implement inefficient combinations of practices. As with conscious choice by managers, this will reduce the share of off-diagonal observations and weaken the power of the performance test. Of course, in either of these cases, the very fact that the practices are correlated provides evidence of complementarities. This suggest a second test for complementarities using the correlation of practices:

\[
\kappa_c = \text{Correlation}(y_1, y_2)
\]

A larger value of \(\kappa_c\) provides more evidence against the null hypothesis of no complementarities. If other exogenous factors affect the choices, then this correlation should be made conditional on those factors.

In many cases, it can be useful to think of this test as estimating a factor demand equation: the demand for one practice, \(y_1\), will be higher when the levels of the other practice, \(y_2\), are higher, conditional on other observable characteristics. If \(y_2\) is determined exogenously, then a multivariate regression will provide an estimate of \(\kappa_c\). When \(y_2\) is endogenous, then it may be possible to identify exogenous instrumental variables and use two stage least squares.

Measuring the correlation, or “clustering,” of practices is perhaps the most common approach to testing for complementarities. It has the virtue that it does not require performance metrics, only observability of the practices themselves. Arora and
Gambardella (1990) were the first explicitly use this fact as a test for complementarities, and it was further analyzed by Holmstrom and Milgrom (1994). See also Arora (1996).

### 4.3 Boundedly-Rational Decision-making: Random Error

While the extreme cases of random and independent assignment of practices on one hand, or perfectly correlated choices on the other hand are useful brackets, most real world cases are likely to fall somewhere in between. In part, this reflects the fact that decision-makers may have imperfect information or bounded capabilities to assess the optimal levels of each practice. Furthermore, they may not be optimizing the same performance metric that the econometrician is measuring. If the choice of the practices reflect both some degree of random error and some degree of conscious choice, then both tests may be useful.

The correlation test, \( \kappa_c > 0 \), has the most power when managers know about the relevant complementarities and are able to act effectively on that knowledge so that errors in choosing practices are small. Conversely, the performance-based test, \( \kappa_p > 0 \), is most powerful when the practices are randomly determined.

In practice, both tests are often useful. For instance, Ichniowski, Shaw and Prennushi’s (1997) analysis presented data on both the clustering of practices and the performance effects of certain clusters. Similarly, Bresnahan, Brynjolfsson and Hitt’s (2002) analysis of information technology and organizational practices included a series of 2x2 charts. The productivity differences relative to the base case of low IT and low adoption of new organizational practices are consistent with complementarities as measured by the performance test \( \kappa_p = f(1,1) + f(0,0) - f(1,0) - f(0,1) = 0.0255 > 0 \) but
the magnitude is not statistically significant.\footnote{Note that the output increase for the High Org/High IT Quadrant (.0643) is significantly greater than in the Low Org/Low IT Quadrant, and is also greater than any of the other strategies. However, this does not by itself indicate complementarity unless the output changes exceed the sum of changes in the off-diagonal quadrants.} At the same time, the disproportionate share of observations on the diagonal (Low-Low, or High-High) cells is consistent with correlation test of complementarities and is statistically significant (Pearson Chi-Square Test for Association: \( \chi^2 = 10.58 \) (p<.001)).

Table 2: Productivity differences for four combinations of IT and organizational practices, Bresnahan, Brynjolfsson and Hitt (2002).

<table>
<thead>
<tr>
<th></th>
<th>IT</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(.0188)</td>
<td>(.0174)</td>
</tr>
<tr>
<td>High</td>
<td>.0258</td>
<td></td>
<td>.0643</td>
</tr>
<tr>
<td></td>
<td>[N=67]</td>
<td>[N=97]</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>0</td>
<td>(.0130)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(n/a)</td>
<td>(.0178)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[N=97]</td>
<td>[N=68]</td>
<td></td>
</tr>
</tbody>
</table>

Standard errors in parenthesis. Number of observations in brackets.

Table 2 matches the organizational data to 1994 IT spending by the same firms. In contrast, when 1987 data are used, the performance test is significantly greater than zero while the correlation test is positive, but not statistically significant. One interpretation is that that managers learned and adjusted their IT investments over the intervening 7 years, which is consistent with optimizing behavior, and which would affect the two complementarities tests as predicted.
4.4 Unobserved Heterogeneity

Problems created by unobserved heterogeneity are particularly salient when examining complementarities in organizations.

The adoption of practices will be a function of their costs and benefits, just as decisions about physical inputs are. However, while the prices of physical capital or labor are often observable, the costs of adopting organizational practices usually are not.

In general, the firm, but not the econometrician, may observe a broad set of exogenous variables. These might be, for example, managerial talent, worker attitudes, or beliefs about market conditions. When these cannot be explained by observables, but still affect the marginal returns to adoption, then the econometric estimates of complementarities can be biased. The standard econometrics of production functions and demand equations (e.g. see Berndt, 1991) can provide useful guidance on potential biases, as can the broader literature on the effects of unobserved heterogeneity and endogeneity in regression estimates.

In particular, Athey and Stern (1998), drawing in part on the work on discrete choice and switching regressions (e.g. Heckman and MaCurdy, 1986; Heckman and Honore, 1990) carefully analyze how unobserved heterogeneity can bias the performance and correlation tests for complementarities we described above. In this subsection, we closely follow their approach to replicate key insights from their model and summarize some of their important results in this section. We refer the interested reader to their very thorough paper for further detail.
Complementarity in Organizations

For simplicity, assume firm $i$ makes a discrete 0-1 choice for each practice and the practices are endogenously determined by the firms’ managers. As above, let $y_1$ and $y_2$ represent Practice 1 and Practice 2 respectively, for example:

- $y_1$: A new computer system.
- $y_2$: A training course.

Let $X$ represent the practice-specific exogenous variables that, regardless of the other practices that the firm adopts, will affect the returns to that practice. For example, worker familiarity with computers will affect the returns to investing in the new computer system. An important assumption is that, regardless of what other practices the firm has in place, these practice-specific variables will affect the returns to adopting that practice.

In particular, the practice-specific return for each practice is:

- $\beta_1 X_1$ if the firm adopts Practice 1, and
- $\beta_2 X_2$ if the firm adopts Practice 2

Now we have described $X$, the variables that affect the returns to the practices.

In addition, there also may be factors that affect adoption but not productivity. For example, training subsidies will make it more likely that the firm adopts training programs, but the subsidies themselves do not directly affect productivity. Let $W$ represent these practice-specific exogenous variables that will affect adoption. Similar to the case for $X$, an important assumption is that these are practice specific variables, and affect the adoption choice for the practice irrespective of what other elements are adopted.
4.4.1 Observability and Bias

Consider the case where the firm is aware of benefits or costs of adopting practices that the econometrician cannot observe. Thus, following Athey and Stern (1998), we further parse the elements of exogenous variation \((X,W)\) each into an observed component and an unobserved component:

Let \(X_j = (x_j, \chi_j)\) for Practice \(j\) \((j = 1,2)\)

Let \(W_j = (w_j, \omega_j)\) for Practice \(j\) \((j = 1,2)\)

The following table is an example of the observed components \((x,w)\) and unobserved components \((\chi,\omega)\) of exogenous variation for adopting Practice 1, a computer system:

**Table 3: Examples of Observable and Unobservable Exogenous Variation in Adopting Computers**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Observable</th>
<th>Unobservable</th>
</tr>
</thead>
<tbody>
<tr>
<td>(X)</td>
<td>(x_j)</td>
<td>(\chi_j)</td>
</tr>
<tr>
<td></td>
<td>e.g. Years of experience; Education</td>
<td>e.g. Home use of computers; Whether software is user-friendly.</td>
</tr>
<tr>
<td>(W)</td>
<td>(w_j)</td>
<td>(\omega_j)</td>
</tr>
<tr>
<td></td>
<td>e.g. State or Federal tax laws to subsidize technology investment; Regulation requiring use of a particular technology</td>
<td>e.g. Beliefs about whether computer system will be adopted by other firms (for example, if network effects are present); Manager inclination to adopt fads.</td>
</tr>
</tbody>
</table>

The observable factors can be incorporated into the estimating equations. However, depending on the nature of the *unobserved* heterogeneity, econometric approaches may be biased to either overestimate or underestimate complementarity.
Consider an estimate of complementarity parameter from interaction effects in OLS or 2SLS estimation of the organizational design production function.

Assume that the interaction effects are constant across firms and let this be labeled as $\theta_{ij}$ where the first subscript indexes the level of the first practice, 0 or 1, and the second subscript indexes the level of the second practice.

The total payoff for each of the four systems will now consist of three components:

1. The direct effect of practice one, if it is present,
2. The direct effect of practice two, if it is present, and
3. The pure interaction effect $\theta_{ij}$ for the relevant system,

This yields the following estimating equation:

$$f^i(i,j) = \beta_1 x_1 y_1 + \beta_2 x_2 y_2 + \theta_{ij} + \xi$$

(11)

Where $x$ represents the observables, and $y$ is a dummy variable that is equal to 1 if the firm adopts the practice, and $\theta_{ij}$ is the pure interaction effect. This above equation is similar to the approach of Ichniowski, Shaw and Prennushi (1997).

As Athey and Stern (1998) point out, we can further break up the error into the following terms:

$$\xi_t = \chi_{1t} y_{1t} + \chi_{2t} y_{2t} + \epsilon_t$$

(12)

So,

$$f^i(0,0) = \theta_{00} + \epsilon_t$$

if the system = (0,0)

---

12 In other words, assume that there is no systematic variation across firms in the performance effects of interactions. We discuss implications of relaxing this assumption in section 4.4.4 below.
The problem is that \( \chi_1 \) and \( \chi_2 \) are unobservable. For example, the ordinary least squares estimate of the payoff from adopting both practices together, \( \hat{\theta}_{11}^{\text{OLS}} \), will have two bias terms (one each from \( \chi_1 \) and \( \chi_2 \)).

Now recall the complementarity test discussed in section 4.1:

\[
\kappa_p \equiv f(1,1) + f(0,0) - f(1,0) - f(0,1)
\]

The expected value of the test statistic will be:

\[
E[\hat{\kappa}^{\text{OLS}}] = \kappa + E[\chi_1_{ij} = (1,1)] + E[\chi_2_{ij} = (1,1)] - E[\chi_1_{ij} = (1,0)] - E[\chi_2_{ij} = (0,1)]
\]

The last four terms add up to zero only if \( \kappa_p = 0 \) and \( \chi_1 \) and \( \chi_2 \) are uncorrelated or are equal to zero. Otherwise, there is bias, which we explore below.

### 4.4.2 Biases in the Performance Test

Under reasonable assumptions, the performance tests may reject the existence of complementarities even when they actually exist. Consider the following assumptions (Athey and Stern 1998, p.18):

1. Assume there are no unobserved exogenous drivers of adoption for the practices: \( \omega_1 = \omega_2 = 0 \).
2. \( \chi_1 \) and \( \chi_2 \) are uncorrelated
3. And, suppose the practices are truly complements \( \kappa_p > 0 \)
Then,

\[ E[\hat{\kappa}_{p}^{OLS}] < \kappa_{p} \quad \text{and} \quad E[\hat{\kappa}_{p}^{2SLS}] < \kappa_{p} \]

This may seem to be a bit counterintuitive. Why should the existence of uncorrelated \( \chi_{1} \) and \( \chi_{2} \) bias the statistic downwards, leading us to possibly reject complementarities when in actuality, they would exist?

To see the problem, write the test statistic as follows:

\[
E[\hat{\kappa}_{p}^{OLS}] = \kappa_{p} + E[\chi_{1}|ij = (1,1)] - E[\chi_{1}|ij = (1,0)] + E[\chi_{2}|ij = (1,1)] - E[\chi_{2}|ij = (0,1)]
\]

Consider the first term after \( \kappa_{p} \). When a firm has adopted both practices, and the practices are truly complementary, then a manager is more likely to find it beneficial to adopt the new computer system even if there not much of an unobserved shock, \( \chi_{1} \). Now examine the second term. If there is no training, and the practices are complementary, then the manager is less likely to adopt the computer system unless there is a beneficial unobserved productivity shock, \( \chi_{1} \). Take an extreme case and suppose that, unless there is training, the econometrician has good reason to believe from the observed variables that the firm is worse off adopting computers than not adopting. Therefore, assuming that the manager is optimizing, if the firm adopts computers but not training, there must have been a large source of unobserved benefits to adopting computers that the manager was aware of, but the econometrician did not see.

Therefore, \( E[\chi_{1}|ij = (1,0)] > E[\chi_{1}|ij = (1,1)] \) and so

\[
E[\chi_{1}|ij = (1,1)] - E[\chi_{1}|ij = (1,0)] < 0 .
\]

Using similar reasoning, \( E[\chi_{2}|ij = (0,1)] > E[\chi_{2}|ij = (1,1)] \) and so

\[
E[\chi_{2}|ij = (1,1)] - E[\chi_{2}|ij = (0,1)] < 0 .
\]
Thus, when the manager is optimizing and faces practice-specific productivity shocks that are unobserved to the econometrician, then the sum of the four last terms is always negative, biasing down the test statistic.

As a practical example, this might be the case if spare computer capacity can be leased out at some firms, generating additional profits from computer purchases for those firms, but not others. Then some firms (those with leasing opportunities) will choose to purchase computers even when the complementary practice (training) is not present. On the other hand, firms which already have a training system in place are more likely to find it profitable to purchase computers, even when they don’t have any additional profits from leasing opportunities. If the econometrician does not observe these leasing opportunities, then the test statistic can be biased downwards.

### 4.4.3 Biases in the Correlation Test

1. Assume there are no unobserved exogenous drivers of adoption for the practices: \( \omega_1 = \omega_2 = 0 \).

2. Assume that \( \chi_1 \) and \( \chi_2 \) are positively correlated (not independent as before)

3. And, assume that the practices are truly independent, \( \kappa_p = 0 \)

Then,

\[ E[\hat{\kappa}_{OLS}^c] > 0 \quad \text{and} \quad E[\hat{\kappa}_{2SLS}^c] > \kappa \]

That is, the researcher would find that there is a correlation between the practices even though there are no complementarities between them.
With these assumptions, the unobserved returns to the new computer system could be high when the unobserved returns to training are also high. For example, it might be that firms in information intensive industries have higher returns to computer investments. Similarly, they might also have greater benefits from training their workers. Then computer purchases would disproportionately occur if $\chi_1$ is high, which is exactly when $\chi_2$ is high as well, leading to greater training.

This can be thought of as a basic case of omitted variables bias. Obviously, if such variables potential exist, the econometrician should make every effort to measure them (i.e. convert them from $\chi$ to $x$) and explicitly include them in the regression.

4.4.4 Systems of Equations and Instruments

Organizational practices can be thought of as inputs to production, much like labor, capital, materials and other inputs. They have costs and generate output, when combined with the right combination of matching practices. Accordingly, the potential biases in estimating equations for the effects of organizational practices have direct analogs in production functions and factor demand equations. This means we can look to those theories for tools to address these biases.

For instance, the bias in the performance equation, as discussed above, arises because choice of practices is endogenously determined. Higher levels of one practice will lead to higher levels of a complementarity practice. However, if all the exogenous drivers, $W$, can be identified for the practices, then these drivers can be used as instruments and a two-stage regression can be estimated. In essence, the econometrician first estimates a demand equation for $X$, which includes all the exogenous determinants of the practice level. If the instruments are valid, then this approach may eliminate the
endogeneity problem and thereby eliminate the resulting bias from these particular unobservables in the performance equation.

If the econometrician has insight into the specific structure of the production function and the relationships among the variables, then a more structural model can be estimated. In particular, the performance equation and the demand equation can be simultaneously estimated as a system of equations with appropriate cross equation restrictions (See e.g. Berndt, 1991, Chapter 9, for a general discussion of this approach).

4.4.5 System-specific variables

Just as there may be unobservables that are correlated with specific practices, there may also be unobservables that are correlated with specific systems of practices, even if they are not correlated with the practices themselves. Unfortunately, by positing a set of unobserved productivity shocks with a suitable pattern of correlations, one can derive any type of bias at all.

For instance, suppose firms that allocate budgets based on a centralized rule gain no benefit from investing in training when they also buy computers – then there is no true complementarity. However, suppose that they tend to either invest in both practices or neither practices proportionately (because of the standardized budgeting rule, such as spending a fixed percentage of last year’s sales on each new practice). In that case, one can see that if having the centralized rule happens to be correlated with greater output, for reasons having nothing to do with complementarities, then both of the complementarities test statistics will be biased toward finding complementarities. Firms will be more likely to adopt one practice when they adopt the other, and firms with higher performance will
be more likely to adopt the practices together than separately. Of course, the opposite bias is equally easy to imagine. If the centralized budgeting rule is correlated with lower performance, then firms that adopt the practices together will have a negative productivity shock, biasing the performance test against finding complementarities even while the correlation test is biased toward finding them.

In most settings, with a little creativity and effort, one can imagine all manner of unobserved variables that add or subtract performance to certain clusters of practices or which create correlations among certain practices, yet are unrelated to direct complementarities. This fact underscores the importance of the econometrician having genuine domain knowledge of the particular set of practices he or she is studying. In the abstract, with zero knowledge, any pattern of unobservable productivity shocks is theoretically possible, and thus any type of bias is possible. Insofar as unobservables cannot, by definition, be measured, there cannot be a purely econometric solution to this concern. Instead, the researcher needs to gain sufficient expertise regarding the setting to be confident that all the relevant variables are included in the model and that specific, plausible alternative explanations are duly considered and assessed. A convincing analysis will rarely, if ever, rely solely on econometric evidence.

---

13 In some cases, it may make sense to expand the system of practices that are considered potential complements to include such a third factor. For instance, it may be plausible that the correlation between a decision-making rule and certain clusters of practices is not due to chance, but rather reflects some complementarity between the practices and this type of decision-making itself. In that case, the interesting question may not be whether or not the complementarities exist, but rather what is the mechanism through which they work.
4.5 **Mitigating Unobserved Heterogeneity**

Because unobserved heterogeneity can seriously undermine estimates of complementarities, it is important to address it. There are four principal approaches to mitigating the effects of unobserved heterogeneity: Homogeneous Populations, Panel Data, Natural Experiments, and Designed Experiments.

4.5.1 **Homogeneous Populations**

The researcher can remove as much unobserved variation as possible *ex ante* by focusing on homogeneous populations. This makes it possible to specify narrow productions functions and narrow performance metrics that are tightly linked to the underlying factor changes.

For example, Ichniowski, Shaw and Prennushi (1997) deliberately limited their analysis to organizations with nearly identical production processes and outputs in order to eliminate most sources of heterogeneity even before beginning their analysis. Bartel, Ichniowski and Shaw (2004) and Ichniowski and Shaw (2003) provide good reviews of “insider econometrics” which often employs this approach.

An important benefit of this approach is that it makes it possible to specify a narrow performance metric that is specifically adapted to the production process being studied. In this case, rather than look at overall market value, profits, or sales, each of which could be affected by a variety of outside, and often unobservable, factors, Ichniowski, Shaw and Prennushi measure the “uptime” of the production line. Based on visits and interviews at the production sites, they determined that the proportion of time that a line was actually running, as opposed to being down for some reason, was almost uniquely determinative of its performance. Accordingly, focusing on this particular
metric provided a sufficient statistic for performance without contamination from other factors. Subsequently, Bartel, Ichniowski and Shaw (2007) took a similar approach in a longitudinal study of 212 plants in the valve manufacturing industry. They looked at several distinct performance metrics, each one matched to a predicted effect of a specific type of information technology. They found evidence that information technology increased productivity via its complementarities with certain business strategies (more customization and smaller batches), human capital, and new human resource practices.

While this approach is very powerful, it is not without its weaknesses. First, it requires a suitably homogenous population. Second, the very narrowness of the production function implies that the results may not be readily applicable to other settings. Finally, unobservables may still play a critical role. For instance, the choices of different work practices at different mini-mills may have reflected differential (perceived) costs of adoption, differential (perceived) benefits, or random error. Without knowing exactly what factors drove adoption, it is difficult to assess the strength of the evidence for complementarities. Furthermore, while the homogeneous population may reduce the unobserved heterogeneity, it is also likely to reduce the observed variation which drives the regressions of interest, so the signal to noise ratio may not be improved as much as hoped. As the late Zvi Griliches once remarked, when one slices the data more and more finely, one often discovers a fractal-like self-symmetry on smaller scales leaving the ratio of observable and unobservable economic phenomena relatively unaffected.

4.5.2 Panel Data
While focusing on narrow productions functions comes at the cost of
generalizability, in some cases one can get the best of both worlds. One way to look at
multiple industries while still controlling for heterogeneity to some extent is to use panel
data. In particular, including fixed effects or taking long differences can remove
potential biases from unobserved heterogeneity whenever the effects of the unobserved
variables do not change over time. In this way, a much larger and more diverse sample
can be studied.

An example of this strategy is the quantification of IT-related organizational
capital at 272 U.S. firms by Brynjolfsson, Hitt and Yang (2002). The firms were in a
variety of industries and each began with its own, idiosyncratic combination of
observable and unobservable characteristics. To address the unobservables, the authors
estimated a specification with firm fixed effects. Thus, a firm with unusually high market
value due to any unobservables that were invariant over time would not be credited with
this high value when assessing the interaction of observable organizational practices and
IT. A similar argument applied to their analysis of long-differences. This specification
subtracted out the historical levels of each of the variables and only examined changes in
these variables.

A benefit of this approach is that it is possible to detect patterns that show up
across numerous industries. This increases the likelihood that similar patterns will hold
outside the sample, and it makes it easier to make fairly general statements about
characteristics of the economy as a whole. It also can make it easier to gather larger
samples, since the units of observation are not constrained to be as similar ex ante.
However, there are also some important weaknesses. First, the fixed effects or long differences will not control for unobservables that change over time. Obviously, a change in one or more of these unobservables can bias the results if it is correlated with the observed variables being studied and if it has an effect on either the levels of the other potential complements (creating a spurious correlation or lack of correlation), or on performance (affecting the productivity regressions). In particular, the same issue of unknown drivers re-occurs as it did when using homogeneous populations.

Secondly, the production functions themselves remain heterogeneous. As a result, the same shock may affect the observed variables in different ways across different firms. For instance, suppose that there is strong complementarity among certain inputs in some firms, while those same inputs are substitutes in other firms that have different production functions. The net result may be that, when the data are aggregated, none of the tests show evidence of complementarity.

The researcher can never eliminate either of these potential problems, but can mitigate them by a) including as many relevant drivers of performance and input demand in the set of observed variables as possible, and b) explicitly identifying the shocks or drivers that lead to changes in their levels, and distinguishing their effects in relevant subsamples of the data. The more sharply defined these exogenous shocks are, the less likely it is that they are coincident with an unobservable.

4.5.3 Natural Experiments

If the researcher can clearly identify an exogenous source of variation in the observable factors, then the potential role of unobserved drivers can be greatly reduced.
The importance of explicitly identifying the sources of changes in the factors is often overlooked, but should be an indispensable component of empirical research on complementarities.

There are several categories of change that can provide the requisite drivers of variation. For instance, legal and institutional changes are often ideal candidates to consider, because a change in a law or government policy can provide a precise date and specific geographic area or jurisdiction for which the change occurs. Given the power of the state, the costs of non-compliance can be extremely high, which also creates a sharp contrast before and after the change. Athey and Stern’s (2002) study of the introduction of Enhanced 911 service is an excellent example of this type of exogenous variation. Advances in information technology made it possible to identify the location of emergency callers. However, by government edict, the adoption was phased in county by county across the state of Pennsylvania, making it possible to identify the changes in complementary activities and several specific outcome measures before and after the adoption of the technology. Given the known government policy change, endogeneity and unobservables could be virtually ruled out as causing the adoption of the technology, making it much easier to make causal inferences about its effects. Each year, cities, states, nations and other government entities introduce, modify or repeal thousands of regulations and laws that can affect the relative costs and benefits of different organizational practices. Many are promising candidates for exogenous drivers, although researchers must be cognizant that some of the legal changes themselves are endogenous to the organizational changes. For instance, differences in minimum wage laws may, in part, be influenced by the differences in the industry mix or organizational practices.
across state lines, or even changes in the relative importance, and political power, of different industries over time.

The introduction of management practices across plants by a multinational corporation can also provide a source of exogenous variation. For instance, the Bloom, Sadun and Van Reenan (2007) study, as described earlier, use data from a set of establishments in the United Kingdom and trace ownership of the parent company to the country where it is based. Because the plants in the study were from the same geography, the institutional differences, derived from the nationalities of their owners, provided a valuable source of identification for the observed differences in technology use and performance.

Technology and resource price shocks are particularly promising candidates. As noted in section 2.2.4, the definition of complementarity in demand theory is that increasing the price of an input reduces the demand for complementary inputs. For example, an increase in the price of oil would be expected to decrease the demand for complements to oil, which might include energy-intensive methods of production and organizational practices. For instance, commuting by car and travel by jet might be replaced by telecommuting and videoconferencing. This in turn, might affect the attractiveness of other organizational complements, such as the types of incentive systems used, the way tasks are allocated across jobs, and the criteria for hiring and training. A technology shock that reduced the costs of electronic interactions might have similar effects on telecommuting and videoconferencing, and thereby, the associated complements. Accordingly, shocks to the price of oil or sudden innovations in technology are likely to be useful for identifying the reasons for changes in the other
complements, especially if the shocks vary cross-sectionally in an observable way. For instance, a multi-establishment firm that rolls out a new technology across the firm over a period of months or years can create a natural experiment, particularly if the roll out is randomized or at least uncorrelated with the variables of interest. The larger, more precisely timed, and more numerous the exogenous shocks, the better, since they are then more likely to overwhelm other, unobservable drivers of adoption.

In each of these cases, an exogenous shock can address the identification issue. Of course, the econometrician needs to make the case that the shock is truly exogenous.

### 4.5.4 Designed Experiments

Last but not least, there are increasing opportunities for economists to participate in designed experiments. This is, of course, the gold standard for research in the natural sciences. However, given that economists typically study organizations with large number of humans and millions or billions of dollars of assets, it has historically been beyond their power, or budgets, to run controlled experiments to test organizational hypotheses. However, the opportunities for such experiments are growing, and under-exploited. In particular, more and more managers today have analytical backgrounds, springing from more formal training in quantitative methods in MBA and other educational programs. As a result, they are already carrying out controlled experiments to assess alternative policies in the course of their decision-making. This is especially prevalent in direct marketing and Internet retailing policies, but also occurs with work practices and technology adoption. For instance, Gary Loveman, CEO of Harrah’s, who has a PhD in economics, regularly experiments with alternative incentive and promotion
programs for employees and customers. Harrah’s gathers copious data from these tests and uses them to design and implement new policies. Similarly, Amazon continuously experiments in both subtle and radical ways with its web design, pricing, delivery options, product selection, recommendation tools, and new features, both individually and in combination with each other. At both companies, the richness and complexity of the choice set provide ample opportunities for identifying potential complementarities. While these two firms are unusual in their commitment to experimentation, they are from unique.

Historically, the costs of large-scale field experiments have discouraged economists from relying on them for data gathering. However, by using data from experiments already conducted by business managers, or better yet, coordinating with them in advance to design more careful experiments, the cost issue can be overcome. When the manager is genuinely uncertain about the optimal policy combination, a well-designed experiment can pay for itself many times over, since the better-informed decisions following the experiment are more likely to be profitable than uninformed choice. Hence, managers can benefit as much, or more, from joint work with academic researchers as the academics can.

For example, Bhansali and Brynjolfsson (2007) worked with a large insurance firm to analyze the effects of a new electronic document management system on work practices, time use and performance. The company had employees in locations across the country engaged in largely identical claims processing work. They phased in the technology at different offices over time and allowed the researchers to gather data pre- and post-implementation, as well as accessing historical data. The resulting quasi-
experiment not only addressed many causality issues, but also made it possible to compare practices and productivity both across time and across different locations. As a result, the correlation of technology use with decreased routine work, increased cognitive work, and higher performance on several performance measures was much easier to interpret.

More recently, Bloom, Genakos, Sadun and Van Reenen (2011), and Bloom, Eifert, Mahajan, McKenzie and Roberts (2009) have conducted randomized control trials in textile firms in India. The treatment was to offer organizational consulting advice to a random sample of the firms. They found that the treated firm became more computerized and more decentralized in their decision-making, consistent with earlier findings about the complementarity of these practices. In turn, average productivity increased by about 10% higher after the treatment, reflecting improved quality and reduced inventories.

The growing success of the experimental approach in addressing issues of causality is underscored by the large number of field experiments are reviewed in the chapter on Personnel Experiments by Lazear and Oyer (2011).

5 Conclusions

5.1 Implications for Managers

Complementarities in organizations can be analyzed rigorously using theory and data, but they also have important practical relevance for managers, and those who educate or advise them. For instance, the frameworks and approaches we review in this chapter can provide insights into:
• Choices about organizational practice,
• Change management,
• Competitive strategy,
• Mergers and acquisitions, and
• Leadership and culture.

Managers are deluged with examples of “best practice,” yet when they implement these same practices at their own firms, they rarely have as much success as the exemplar that they seek to imitate. Complementarities can help us explain why. The success of a practice almost always depends on the system of complementary practices in which it is embedded. Thus, the concept of “best practice”, devoid of context, can be misleading. The same piece rate pay rules that work so well at Lincoln electric may end up undermining performance if implemented a la carte into another organization. Thus, before implementing a new incentive system, hiring practice, training program or technology, managers should explicitly consider the existence or absence of the relevant complements. Of course, specifically identifying the relevant complements will often be non-trivial, but merely being aware of their relevance is a necessary first step.

A fruitful application of the theory of complementarities has been to change management. In particular, taking advantage of new technologies or other innovations typically requires substantial changes in a broad set of related business practices. Insights into the optimal pace, sequence, location, and even feasibility of change efforts can be provided by analyzing the situation from the perspective of complementarities. While the mathematics of complementarities can be daunting, the underlying concepts are not hard
for managers to grasp and manipulate. For instance, the “Matrix of Change” tool
(Brynjolfsson, Renshaw and Van Alstyne, 1997) mentioned in Section 1 has been used
by thousands of managers to make explicit organizational complementarities that might
otherwise remain hidden. Appendix B provides a simple illustration.

Complementarities can also affect competitive strategy by creating lasting entry
barriers and accompanying rents. As the Lincoln Electric case illustrates, best practices
can be difficult to imitate if they rely on a web of interactions with other practices for
success. As Milgrom and Roberts (1990) point out, this gives economic content and
rigor to the concept of “core competence.” Ironically, as noted by Roberts (2004),
organizations that succeed in implementing tightly coupled systems of highly
complementary practices may have the greatest difficulty adopting new combination of
practices when external factors warrant a change.

Complementarities among organizational practices create risks in mergers and
acquisitions. The real value of many, perhaps most, businesses lies not in their tangible
assets, but in their intangible organizational capital. But this organizational capital can be
fragile; the practices that are successful in one setting may not be so anymore after being
meshed with different practices in a merger or acquisition. Understanding the role of
complementarities in organizations can make this management task less mysterious and
more manageable.

Finally, leadership and culture might be thought of as far removed from
quantitative analysis, and in many ways they are. However, an understanding of
complementarities can illustrate why and when a clear leadership vision and strong
organizational culture can be most beneficial. When practices are complementary, there
are multiple equilibria. Coordinating on one of these equilibria, even if it’s not the global optimum, will often be more successful than choosing practices in a decentralized and uncoordinated way. In contrast, optimizing individual practices on their own does not necessarily maximize total firm performance. This is suggests a clear role for leadership and culture. This task becomes even more important when conditions call for moving from one equilibrium to another one. Just as complementarities can create inertia to prevent change, they can also create momentum for a virtuous cycle of change – if the right set of practices is changed first.

Historically, the theory and analytical tools developed in economics and related disciplines have provided clear guidelines for managers who wish to use quantitative analysis instead of just heuristics and instincts to manage and price physical assets and technologies. The formal analysis of organizational complementarities promises to do the same for a much broader set of management challenges facing companies today.

## 5.2 An Agenda for Economists

There are at least three major frontiers for economic research on complementarities in organizations that overlap with one another: applications of existing theory, empirical assessments of complementarities, and extensions of the theory.

### 5.2.1 Applications of the theory

In some ways, the agenda for economists seeking to advance the frontiers of complementarities research parallels the implications for managers. By identifying
specific sets of complementary practices we may shed light on a remarkably broad range
of economic questions. For example:

- Can organizational complements to new technologies explain changes in
  productivity growth across geography, time, and industry?\(^{14}\)

- Can such complements explain the growth in income inequality and the
demand for certain types of labor or skills?

- Why are firms exiting certain industries and what do they have in common?
  What about entrants, including those with operations in other industries, as
  well as start-ups?

- To what extent do patterns of exports and imports, or regional trade, match the
  geographic distributions of complementary factors?

- How well can complementarities explain the specific set of activities that
  happen inside of firms and those which are outsourced or spun-off? When
  can they explain mergers and acquisitions?

In addition, there may be some general implications of complementarities beyond
those linked to specific practices. If one thinks of organizations as large clusters of
complements, including many which are intangible or subtle, then the theory has several
implications. For instance, when combined with game theory, complementarities can be
a part of a theory of organizational inertia (e.g. Baron, Burton and Hannan, 1996),
explaining why and when change can be difficult. It can be very difficult to coordinate
change on multiple practices when decision-making is decentralized, communication is
imperfect, incentives don’t match output, or all of the above.

\(^{14}\) See e.g. Basu, Oulton and Srinivasan (2003) and Bresnahan and Trajtenberg (1995).
A closely related question is the existence of persistent performance differences among seemingly similar firms (Gibbons, 2006). Subtle complementarities can explain why seemingly similar competitors don’t get the same benefits from activities. If the complements are long-lived, then the systematic performance differences can also be persistent.

Complementarities literally mean that the whole is greater than the sum of its parts, which suggests a role in valuing the “organizational capital” and other intangible assets of firms. While neoclassical theory tends to model firms as productions functions that simply combine various inputs to produce output, complementarities provide an explanation for why a “going concern” may be much more valuable than the same components a la carte. Similarly, by identifying and exploiting complementarities, the overall output of an economy, can consistently exceed the weighted sum of its factor growth rates. In addition, the more heterogeneity there is among inputs, the more combinations are possible, and the potential there is for complementarities.

Finally, the interplay of practices in sustaining a system of complements may shed light on corporate culture. Because of the multiplicity of equilibria that arise when systems have large numbers of potentially complementary practices, a general coordinating device such as culture can play an important role. For instance, it might be possible to extend the Kreps (1986) model of corporate culture by incorporating a more explicit role for complementarities.
5.2.2 Empirical Assessments of Complementarities

Most, if not all, of the applications discussed above lend themselves to empirical work. Embedding econometric work in a complementarities framework can make it easier to develop testable hypotheses.

Thus far, most of the empirical work on complementarities has relied on cross-sectional studies or relatively short panels. However, some of most interesting issues raised by the theory pertain to changes in organizations over time. Thus, there is an opportunity for more work using longer panels and longitudinal data, with attention to entrants, exits and persistence of performance differences.

Methodologically, some of the current frontiers for empirical work on complementarities include:

- Panel data on relatively homogenous populations and clear, exogenous drivers of variation in practices, or preferably, changes in those practices;
- Use of novel metrics of activity and performance, such as fine-grained, practice-specific inputs and outputs;
- Structural modeling of systems of both the performance and demand equations, drawing on significant domain-specific knowledge of the setting, relevant practices and likely interactions; and
- Exploiting and even designing controlled field experiments to isolate the role of changing specific practices.

There has been significant progress in all of these areas. However, the last one, controlled field experiments, may be the most important for eliminating the biases
discussed in Section 4 above and getting a clear quantification of complementarities. There are significant limits to how much can be learned solely by more sophisticated modeling. Fortunately, managers are increasingly receptive to the experimental approach. They are designing and implementing controlled experiments on their own and in cooperation researchers. Part of this reflects the more academic and often quantitative training that managers have today and part reflects the relative flexibility of some new technologies, making controlled roll-outs and careful monitoring of results easier. The success of the experimental approach in interactive marketing has made it more attractive as a way to improve organizational design choices as well.

5.2.3 Extensions of the Basic Theory

There are several ways the theory of complementarities can be extended. One interesting tack is to explore the dynamics of learning and growth in larger systems of complements. As the number of potential organizational complements increases, the number of potentially profitable systems to explore explodes combinatorially. This brings to the fore the issue of efficient search and learning. Learning need not occur primarily or even at all the level of an individual through conscious deliberation. It is also possible that learning occurs at the organizational level, perhaps through a quasi-evolutionary process. For instance, the influential paper by Cohen, March, and Olsen (1971) argued that managerial decisions should not be thought
of as being made rationally, but rather through the random matching of problems and solutions, as if being jostled about in a garbage can.\textsuperscript{15}

In practice, innovative combinations of business practices are sometimes achieved by extensive trial and error. If the production process is complex, with many potentially relevant variables and interactions, it can be very difficult to identify the optimal combinations. Strong complementarities can significantly retard such a process, by reducing the value of local experimentation, especially if the choices are indivisible and non-concave. At the same time, the theory can provide guidance about ways to simplify the search process.

If this mechanism of tinkering is important, then except in environments that have been very stable for a long time, the population of firms will exhibit a variety of different strategies, including both successful and unsuccessful ones. As argued by Nelson and Winter (1982), successful systems may increase their share of the population of firms if they survive longer or attract more imitation. However, the most profitable combinations will not necessarily be the ones that dominate the population (see e.g. Cowperthwaite et al., 2008). There is recent evidence that design modularity can affect the nature and speed of this evolution by bundling together complementary components (MacCormack, Rusnak, and Baldwin 2008), and complementarities can create momentum as well as inertia (Milgrom, Qian and Roberts, 1991), but a comprehensive theory remains to be developed.

In conclusion, there is a plethora of opportunities for further research using the tools and insights of complementarities in organizations. Such research may shed light

\textsuperscript{15} See also Levinthal and March (1981)
on some of the long-standing puzzles and challenges that have confronted economists and others who study organizations.
References


Argyris, Chris, Organizational Dynamics, 1982.


Baron, James N.; Burton M. Diane and Hannan, Michael T. “Inertia and Change in the Early Years: Employment Relations in Young, High Technology Firms,” Industrial and Corporate Change, 1996.


Ennen, Edgar and Richter, Ansgar. "The Whole is More than the Sum of its Parts -- or is It?" Working Paper, European Business School, 09-07.


Complementarity in Organizations


## Appendix A: Empirical Papers

<table>
<thead>
<tr>
<th>Complementarities</th>
<th>Firm</th>
<th>Plant/Establishment</th>
<th>Prod. Line/Bus. Unit</th>
<th>Individual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision Rights</td>
<td></td>
<td></td>
<td>Arrunada, Garicano and Vazquez (2001)</td>
<td></td>
</tr>
</tbody>
</table>
Appendix B: An Example of the Matrix of Change

When Merrill Lynch’s brokerage business was confronted with competition from online brokers, the company contemplated changing over to an all-electronic approach. Although the technology itself was relatively straightforward, it was clear that the associated complementary changes that would also need to be made would be traumatic. In addition to physical stores, the existing brokerage business had several other important characteristics: assignment of a personal broker to each client, relatively high fees, using the human broker to mediate trades, provision of investment recommendations, heavy investment in an in-house research staff, and focus on a relatively limited, high net worth client base. Every one of these characteristics was eliminated in the reigning approach to electronic trading, and a new set of practices was implemented.

The Matrix of Change analysis showed that the old practices formed a coherent system of mutual complements. The new system also was dominated by complementary interactions. However, interactions between the old and new practices were rarely complementary and more often conflicted with one another. The Matrix of Change tool illustrated these effects by denoting complementary interactions with “+”, and conflicts with “-” as described in figure B1 below.

The complementarities in the old system suggest it would have a great deal of inertia while the conflicts in the transition matrix suggest that an organization which tried to run with a mixture of old and new practices would be relatively inefficient. Hence, the change effort would likely be difficult and there were relatively few synergies between the old and new system. Finally, it was clear that the new system was itself fairly coherent, but perhaps not quite as much as the old system. These insights, while drawing on complementarity theory, can be visualized easily without and formal economic or mathematical analysis.
Figure B1: A Matrix of Change Analysis for the transition from traditional brokerage to online brokerage.