AN INCOMPLETE CONTRACTS THEORY OF INFORMATION, TECHNOLOGY AND ORGANIZATION

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ABSTRACT

Although there is good reason to expect that the growth of information work and information technology will significantly affect the trade-offs inherent in different structures for organizing work, the theoretical basis for these changes remains poorly understood. This paper seeks to address this gap by analyzing the incentive effects of different ownership arrangement in the spirit of the Grossman-Hart-Moore (GHM) incomplete contracts theory of the firm. A key departure from earlier approaches is the inclusion of a role for an "information asset", analogous to the GHM treatment of property. This approach highlights the organizational significance of information ownership and information technology. For instance, using this framework, one can determine when 1) informed workers are more likely to be owners than employees of firms, 2) increased flexibility of assets will facilitate decentralization, and 3) the need for centralized coordination will lead to centralized ownership. The framework developed sheds light on some of the empirical findings regarding the relationship between information technology and firm size and clarifies the relationship between coordination mechanisms and the optimal distribution of asset ownership. While many implications are still unexplored and untested, building on the incomplete contracts approach appears to be a promising avenue for the careful, methodical analysis of human organizations and the impact of new technologies.

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1. Introduction

Information technology has the potential to significantly affect the structure of organizations. However, the nature of these changes is still being debated. While the heuristics and intuition that managers have applied for years provide some guidance, the changes enabled by information technology are potentially so radical that past experience may not prove a trustworthy guide. Meanwhile, researchers using field studies examining the link between investments in information technology and changes in organizational structure have come to diverse and often contradictory conclusions (see (Attewell & Rule, 1984), and (Crowston & Malone, 1988) for reviews). Econometric work has been able to generalize some of the findings of the case studies, but can only claim to have found correlations, not causal links (Brynjolfsson, Malone, Gurbaxani & Kambil, 1991a). Managers and researchers each suffer from the lack of robust theoretical models that provide sharp, testable predictions.

The interdisciplinary field of coordination science has emerged in part to help address this gap. For instance, Malone and colleagues (Malone, et al., 1987; Malone & Smith, 1988; Malone, Yates & Benjamin, 1987), have modeled different structures, such as firms and markets, for coordinating intelligent agents. This has enabled specific predictions of the effects of changes in information technology on the flexibility, production and coordination costs of these structures. However, many important issues concerning information technology and the boundaries of the firm are beyond the scope of these models. In this paper, I pursue a new approach to address the following questions:

1) How does the location of information affect incentives and ownership structure?
2) Do smaller firms provide better incentives for exploiting information?
3) Are flexible assets more appropriate for informed agents?
4) How does "coordination information" affect the optimal distribution and ownership of production assets?

While many of these questions fall under the traditional purview of economics, progress has been hampered by the lack of an adequate economic theory of the firm. Ironically, despite the central role of the firm in economics, neoclassical economics traditionally treats the firm as little more than a black box "production function". Developments in principal-agency theory have given some insight into the incentive

mechanisms used *inside* firms, and by extension, the role of information and information technology. However, because the same models apply equally well to contracts *between* firms, agency theory by itself cannot explain the boundaries of firms or the relative advantages of different institutional or ownership structures.

Transaction cost economics (Williamson, 1975; 1985) directly addresses the question of what determines firm boundaries. The insights of this approach have been useful in describing the impact of information technology on firm boundaries and inform much of the work of Malone and his colleagues (Brynjolfsson, Malone & Gurbaxani, 1988; Malone, Yates & Benjamin, 1987). However, while it is difficult to develop a theory of IT's impact on firm boundaries using agency theory, it is almost too easy using transaction cost economics. As Fischer [1977] put it: "There is a suspicion that almost anything can be rationalized by invoking suitably specified transaction costs."

More recently, a economic theory of the firm has emerged that combines the insights of transaction cost economics regarding the importance of bounded rationality and contracting costs with the rigor of agency theory. The new theory focuses on the way different structures assign property rights to resolve the issues that arise when contracts are incomplete. This provides a basis for defining different organizational structures by the ownership and control of key assets. Grossman, Hart and Moore (Grossman & Hart, 1986; Hart & Moore, 1990; Hart, 1988) pioneered this approach and its relationship to earlier approaches has been lucidly documented by Hart (1989).[1]

In this paper, I build on the insights of the property rights approach to the theory of the firm to clarify the mechanisms by which information technology can be expected to affect the organization of economic activity. In particular, I will consider the incentive effects of various allocations of "information assets" as well as physical assets. By considering the role of incentives, it is possible to strengthen the link between stylized coordination mechanisms and real-world institutions like firms and markets. For instance, this approach facilitates the analysis of cases that illuminate each of the four questions posed above.

The remainder of the paper is organized as follows. Section two describes the basic assumptions behind the property rights approach and sets up the framework. Section three

[1] Holmstrom and Tirole [, 1989 #191], and Hart and Holmstrom [, 1987 #331] also present insightful models and discuss the organizational implications of incomplete contracts and the property rights approach.

uses this framework to explicitly treat information as an asset. This facilitates the investigation of a variety of different organizational forms under different distributions of information, levels of asset specificity and coordination mechanisms. In section four, I summarize the conclusions of the paper and compare and contrast it to related literature.

2. Information and asset ownership

2.1 Background

Before examining specific models of information technology and information work, it is worth sketching the basic tenets of the property rights framework.

Begin by considering one of the simplest sorts of organization, an arrangement between a principal and an agent hired to accomplish some task. As principal-agent theory has long argued, appropriate incentives must be provided for the agent. In general, because the principal cannot directly measure the effort level of the agent, incentives need to be provided by making the agent's pay partially contingent on performance. An example is the commission that a sales agent often receives. A basic conclusion of the theory is that agency problems can be mitigated, and sometimes even solved, by promising the agent a sufficient share of the output produced.

However, problems arise when it is not possible to specify clear performance measures in advance. For instance, the owner of the firm may have insufficient information to prespecify the decision-making activities of the firm's managers (after all, that's presumably what they were hired to do). Simply linking management pay to sales or even profits would encourage managers to inappropriately shift resources away from R&D and maintenance. The solution prescribed by agency theory calls for a comprehensive contract that considers the marginal value of all possible activities of the agents and the marginal cost to the agents in all possible states of the world, and the ability of the principal to commit to pay the appropriate compensation for each outcome (Banker & Kemerer, 1990; Hart & Holmstrom, 1987). Lacking such a comprehensive contract, incentives, and therefore production, will be suboptimal.

A key tenet of the GHM approach is that unlike the contracts typically analyzed by agency theory, real world contracts are almost always "incomplete", in the sense that there are inevitably some circumstances or contingencies that are left out of the contract, because they were either unforeseen or simply too expensive to enumerate in sufficient detail. For instance, the exact words used in a sales pitch to a given customer, the level of intangible

"quality" of a manufactured good, the level of "care" used in maintaining a piece of equipment, or the thought process used in generating a creative insight are all aspects of a contract that are often too costly, if not impossible, to include in a contract. This is a natural consequence of the bounded rationality of the parties. Each of the parties will have certain rights under the contract, but its incompleteness means that there will remain some "residual rights" that are not specified in the contract. When these rights pertain to the use of an asset, the institution which allocates these residual rights of control is property ownership. All rights to the asset not expressly assigned in the contract accrue to someone called the "owner" of the asset.[2] For example, if a machine rental contract says nothing about its maintenance protocol, then it is the machine's owner who retains the right to decide.

The allocation of the residual rights of control will have an important effect on the bargaining position of the parties to the contract after they have made investments in their relationship. In the absence of comprehensive contracts, property rights largely determine which ex post bargaining positions will prevail. In particular, a party that owns all the essential assets will be in a position to reap all benefits from the relationship which were not explicitly allocated in the contract by threatening to withhold the assets otherwise. A party who does not control any assets must rely on the letter of the contract or the goodwill of the assets' owner to share in the output. As a result, an agent who controls no essential assets risks going unpaid for work which is not specifically described in an explicit contract. In contrast, the agent who controls assets that are essential to the relationship can "veto" any allocation of the residual rewards which isn't considered sufficiently favorable. Thus, the ownership of assets that are essential to production and the receipt of the residual income stream go hand in hand.

According to this view, the dilemma of providing incentives to agents when comprehensive contracts are infeasible can be mitigated if those agents are assured a significant share of the output they produce by providing them with the ex post bargaining power inherent in asset ownership. Based on this principle, Grossman, Hart and Moore have derived a theory of vertical and lateral integration with implications for industry structure and the optimal size of firms.

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[2] This is essentially equivalent to the legal definition of ownership. For example, Hart [, 1989 #19] cites [Holmes, 1946 #334] on this. Of course, law and custom may put some bounds on the use of an asset, even by its owner.

2.2 The Hart-Moore framework

The distinction between "markets" and "hierarchies" emphasizes that production can be organized within one firm or among several firms, depending on whether the principal means of production are controlled by a single person or group, or distributed among several. Hart and Moore [, 1988 #112] develop a useful framework and notation for examining how changes in the distribution of asset ownership affects the incentives of the individuals who work, directly or indirectly, with those assets and they establish a number of propositions regarding the optimality of different ownership structures. I will use a variant of this framework to capture the essential properties of the relationship between information and ownership and to provide a useful tool for more broadly examining the organizational implications of different distributions of information among individuals.

Application of the this framework requires a number of assumptions, which are reproduced formally in the appendix. Because ownership is only important to the extent that actions are uncontractible, all actions in the model are assumed to be uncontractible, with incentives influenced only by asset ownership. The cost of agent i's (one dimensional) action, x_i, is given by $c(x_i)$, and the marginal value generated by i's actions when he is in a coalition with a subset S of other agents is denoted $v^i(S,A(S)|x)$, where A(S) is the set of all assets owned by the coalition and x is the vector of actions taken by the coalition's members. To decide how the total value generated by a group of agents working together will be apportioned, Hart and Moore suggest the use of the Shapley value:

$$B_i(a|x) \equiv \sum_{S|i \varepsilon S} p(S) \left[v(S,A|x) - v(S\backslash\{i\}, A(S\backslash\{i\})|x) \right] \qquad (1)$$

where $p(S) \equiv [(s-1)!\ (I-s)!]/I!$

$s \equiv$ the number of agents in a given subset S, and

$I \equiv$ the total number of agents

This amounts to paying each agent an amount equal to his contribution to each potential coalition multiplied by the probability that he will be in any given coalition. Although the Shapley value is traditionally used to analyze cooperative bargaining (Shapley, 1953), Hart and Moore provide a detailed non-cooperative bargaining justification for this assumption and cite related literature. In any event, the exact rule for

division of the surplus will generally have no qualitative effect on the results as long as each agent's share of output is positively correlated with his access to essential assets.

Assets are relavent in Hart and Moore insofar as they affect marginal product; the marginal value of an agent's actions are greater when he has access to more assets:

$$v^i(S,A|x) \geq v^i(S,A'|x) \text{ for all subsets } A' \text{ of } A. \qquad (2)$$

They specifically limit the interpretation of the term "asset" to non- human assets like machines, factories or customer lists because they are alienable, and thus can change "ownership". However, because many assets, such as information, knowledge and skills can be embodied either in humans or in tradeable commodities, I will not automatically exclude "human" assets from consideration. I will argue that the information that an agent knows can be critical to his productivity and incentives, suggesting that human capital can be treated on a par with physical capital. Accordingly, in the examples that follow, I will treat the information that the agent knows as an "asset" that he "owns". This approach will facilitate the analysis of how the inalienability of some assets, such as knowledge, affects the optimal allocation of other assets, such as physical capital. In addition, it will make it possible to analyze the choice to embody assets in more or less "alienable" forms. Furthermore, by assuming that the synergies between agents occur only through the assets (including information) that they have access to, we can simplify the notation by suppressing the explicit reference to the coalition of other agents, as well as the vector of actions, x:

$$v^i(A) \equiv v^i(S,A(S)|x). \qquad (3)$$

3. Information and organizational structure

3.1 How does the location of information affect incentives and ownership structure?

In the first case I examine, agent 1 hires agent 2 who has some information which is necessary to the productivity of the firm. Label the physical aspects of the firm as asset a_F, the information as asset a_I; and assume that neither asset is productive to a person unless he also has access to the other.

Assuming that agent 2 "owns" the information asset, a_I, who should own the physical assets of the firm, a_F?

Each agent will exert effort until the marginal benefit he can expect to receive, as given by his Shapley value, is just equal to the marginal cost of the action he takes. Thus, the first order conditions of agent 1 and agent 2 are given by the following equations.[3] If agent 1 owns the physical assets (and agent 2 owns the information):

$$\text{agent 1:} \quad 1/2\ v^1(a_F, a_I) + 1/2\ v^1(a_F) = c_1'(x_1) \tag{4a}$$

$$\text{agent 2:} \quad 1/2\ v^2(a_F, a_I) + 1/2\ v^2(a_I) = c_2'(x_2) \tag{4b}$$

If the agent 2 owns the physical assets (and the information):

$$\text{agent 1:} \quad 1/2\ v^1(a_F, a_I) = c_1'(x_1) \tag{5a}$$

$$\text{agent 2:} \quad 1/2\ v^2(a_F, a_I) + 1/2\ v^2(a_F, a_I) = c_2'(x_2) \tag{5b}$$

Net benefits will be maximized by providing the strongest[4] incentives for effort on the part of each agent. The organizational problem can thus be viewed as a matter of choosing among the feasible allocations of asset ownership one that maximizes the left hand side of each equation. When the incentives of different agents are maximized by different asset allocations, one will need to consider the relative importance of providing incentives for particular agents and make trade-offs.

If the information and physical assets of the firm are productive only when used together, then the second term in both equation 4a and equation 4b is equal to zero. Thus, the left hand side of equation 4a is equal to the left hand side of equation 5a, meaning that agent 1's incentives are unaffected by a change in asset ownership. However, the incentives for agent 2, as given by equations 4b and 5b, are strictly greater when he owns the physical assets. Thus, from an incentive standpoint, it is optimal to give the agent 2 ownership of the physical assets of the firm as long as he has information that is essential

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[3] The Shapley value for equation 4a can be worked out as follows. There are two coalitions that agent 1 can be a member of, {1,2} and {1}. Each of these coalitions occurs with probability p(s) = 1/2 and in the first coalition, agent 1 has access to both assets, and in the second coalition, he has access only to the physical assets of the firm. Thus his expected share the marginal product of his effort is: $1/2\ v^1(a_F, a_I) + 1/2\ v^1(a_F)$, where $v^i(.)$ is the derivative of total value with respect to a change in agent i's actions. This is equated to the marginal cost of his actions. The derivation of the other first order conditions is analogous.

[4] Given the assumptions, there is no danger of the incentives being too strong. See proposition 0 in Hart and Moore (1990).

to its productivity anyway. Incentive considerations prescribe that the informed agent should be given ownership of the assets necessary to his work.[5]

If agent 2's information is not completely essential to the productivity of the physical assets, then giving him ownership of them will reduce the incentives of agent 1 (5a will be less than 4a). Whether this is outweighed by the improved incentives to the informed agent will be a function of how necessary that agent's information is to the productivity of the firm and how important it is to maximize his incentives relative to those of agent 2. Equations 4 and 5 show that the more important it is to provide incentives to the informed agent, the more likely it is that it will be optimal to give him ownership. Furthermore, to the extent that it is particularly difficult to prespecify the outputs for "information work", it is likely that informed agents will have significant, uncontractible actions.

Explicitly treating information as an asset as modelled in equations 4 and 5 makes it natural to consider a third alternative: giving agent 1 "ownership" of both the physical assets and the information. In certain circumstances, it may be more efficient to move the information to the "principal" agent than to shift ownership of all the physical assets to the hired agent. This yields:

agent 1: $1/2\ v^1(a_F, a_I) + 1/2\ v^1(a_F, a_I) = c_1'(x_1)$ (6a)

agent 2: $1/2\ v^2(a_F, a_I) = c_2'(x_2)$ (6b)[6]

Now the incentives of agent 1 are maximized at the expense of agent 2. This will provide incentives that are superior to those under agent 2's ownership if the actions of agent 1 are relatively important.

However, there are a number of reasons that it may be difficult to transfer the information "asset" to agent 1 (Brynjolfsson, 1990a). Most notably, the reason for hiring

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[5] It is also worth interpreting this result in terms of Hart and Moore (1990). In one sense, it could be considered an application of their proposition 5 that an agent who is "indispensable" to an asset should own that asset. Because the agent in the preceding example has information essential to the productivity of the physical asset, he is effectively "indispensable" by their definition. Given our treatment of information as an asset that is necessary to the productivity of the physical assets, they can appropriately be thought of as complementary assets. This suggests that Hart and Moore's proposition 7 is even more germane: complementary assets should be owned by the same agent.

[6] Alternatively, if the information asset is "copied", we have

agent 2: $1/2\ v^2(a_F, a_I) + 1/2\ v^2(a_I) = c_2'(x_2)$ (6b)'.

an agent in the first place is often to reduce some of the information processing load on the principal. Furthermore, the relevant information may be generated by the hired agent in the course of his activities, as in learning-by-doing, or simply by what Hayek (1945) calls the "knowledge of the particular circumstances of time and place". This information may be costly to convey to the agent 1, not only because of difficulties in codifying and transmitting it, but also because of adverse selection problems. It is notably difficult to consummate transaction when the parties have differential information (Akerlof, 1970; Arrow, 1975).

When, for whatever reason, the information asset cannot be owned by agent 1, yet it is necessary to the productivity of the physical assets, the incentive considerations featured in the preceding analysis suggest that the next best solution will generally be to give ownership of the physical assets to the hired agent. Complementary assets should be owned by the same party, and in this case, this requires moving the alienable physical assets to the inalienable information asset. This will be true even when, ignoring the alienability constraint, the incentives implicit in equations 6a and 6b dominate those provide by equation 5a and 5b. In fact, by comparing the incentives in these two systems of equations provides a way of assessing the value of embodying knowledge in alienable assets.

Hart and Moore also present an argument suggesting that the ownership of assets essential to production is likely to give the owner "authority" over other agents that need access to those assets. Without reproducing their argument, this suggests that a corollary to the proposition that informed agents should own the essential assets is that they are also likely to gain authority over uninformed agents.[7]

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[7] This argument is distinct from, but complementary to, that of Rabin (1988), which also modeled the relationship between information and authority. Instead of examining the incentives of the informed agent to maximize uncontractible effort as is done above (a moral hazard problem), Rabin showed that the adverse selection problem could also be sufficiently severe that, in certain equilibria, an informed agent could only "prove" the value of his information by taking control of the firm and its residual income stream. This leads to the informed agent getting authority over the uninformed agent. Both these considerations may be relevant in some situations. For instance, venture capitalists often insist that an informed entrepreneur hold a significant stake in a new venture, both as a signal of his own faith in the project (adverse selection) and as a motivator to get him to work hard (moral hazard).

3.2 Do smaller firms provide better incentives for exploiting information?

The analysis above considered just one "information" asset and showed that the ownership of physical assets should be collocated with the information necessary to the productivity of those assets.

The possibilities become more interesting when there are multiple, informed agents. Consider the case of n agents (i = 1...n), each of whom has some information (a_i, i = 1 ...n) which requires access to a physical asset (the "firm": a_F), to be productive. Assume that the information of one agent does not affect the information of other agents.

If any one agent, j, is given ownership of the physical asset, his first order condition is:

$$v^j(a_F, a_j) = c_j'(x_j) \qquad (7)$$

The first order conditions of each of the other agents are:

$$1/2\ v^i(a_F, a_i) = c_i'(x_i), \text{ for } i \neq j$$

Regardless of which agent owns the physical asset, *all* the other agents in the firm will have insufficient incentives to exert effort. To the extent that these insufficient incentives will lead them to underutilize their information, overall productivity would be enhanced if the same agent could own all the information and the physical asset of the firm. This is consistent with the notion of providing all the necessary information to the running of the firm to an owner/manager. The owner/manager has the information and the first-best incentives, while the other agents simply carry out his instructions, with little information or physical asset ownership of their own. Because their *uncontractible* actions are kept to a minimum, their is little need to provide them incentives through ownership. This is in many ways consistent with the Taylorist prescription that enable the creation of large, successful hierarchical firms.

An interesting alternative to single agent ownership is to have a partnership, as many professional firms do, in which control of the physical assets is allocated on the basis of majority rule. In this case the agent will effectively control the firm whenever he is in the majority coalition, so (for n odd) his first order condition is:

$$(1/2 (n + 1)/n)v^i(a_F, a_i) = c_i'(x_i) \qquad (8)$$

This system will more evenly allocate the incentives of all the agents. However, they will still have insufficient incentives to invest compared to the first-best, especially as n becomes large.

The problem of insufficient incentives for the informed agents cannot be solved by any combination of voting patterns because there is simply not enough residual income to go around. The first best incentives require that on the margin, each agent receive 100% of his contribution, but this is not possible if only total output is observed and budget balance is to be maintained (Alchian & Demsetz, 1972). This brings us back to the assumption made at the beginning of this section that all actions were not contractible. There is clearly a strong benefit to setting up production so that actions are contractible so that ownership does not have to bear the (impossible) burden of providing incentives for all the agents. Firms obviously do try to regiment production in ways that facilitate this, sometimes at the expense of creative freedom (Holmstrom, 1989).

One can see that small firms are likely to have an advantage in providing incentives, not only because it is likely to be easier to separate out and reward the individual contributions [Holmstrom and Tirole, 1990], but also because even the uncontractible actions will have stronger incentives in smaller firms.[8] For instance, equation (8) indicates that small partnerships will provide stronger incentives than large ones; proprietorships provide the best incentives of all. When it is important to provide incentives for the application of information in ways that cannot be easily foreseen and incorporated into a contract, small firms will have a relative advantage over large firms.

3.3 Are flexible assets more appropriate for informed agents?

The inefficiencies inherent in having multiple informed agents working in the same firm, whether the firm is owned by one of the agents or a partnership, can be alleviated if

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[8] The stronger, output-based incentives for uncontractible actions in smaller firms will not only induce higher effort, but in multidimensional models, less effort on actions that do not enhance output. This supports the conjecture of Geanakoplos and Milgrom (1985): Actual diseconomies of scale in management are likely due to the political incentives of individuals and groups to divert common resources for their own purposes -- incentives which are notably smaller in smaller organizations.

each of the agents could have uncontested ownership of, and therefore access to, the physical assets of the firm.

If the physical assets of the firm are not unique, and if there are no economies of scale in their use, then the first best incentives for all of the informed agents can be costlessly achieved by giving each of them his or her own firm (that is, an a_F asset for each agent with an a_i asset, as in equation 7).

Alternatively, the assets of the firm may be divisible to some extent. In this case, agent i may not need access to all of the physical assets that comprise the firm, but only some subset, a_{Fi}. Then there will be a trade-off between distributing the assets of the firm to its agents or keeping the assets together. To the extent that the firm's assets are complementary, dividing ownership of the assets will reduce their productivity in those coalitions in which they were separated. On the other hand, if each agent's information, a_i, were particularly synergistic with only the subset a_{Fi}, then there are advantages to giving that agent ownership, so that they would always be together.

As an example, consider the case of three agents and three physical assets of the firm, where synergies exist among the firm's assets, and between each agent's information and the firm's assets.

When agent 1 owns the subset of physical assets a_{F1}, (and of course his private information, a_1,) his first order condition is:[9]

$$1/3v^1(a_1, a_{F1},a_{F2},a_{F3}) + 1/6v^1(a_1, a_{F1},a_{F2}) + 1/6v^1(a_1, a_{F1},a_{F3}) + 1/3v^1(a_1, a_{F1}) = c_1'(x_1) \qquad (9)$$

Alternatively, if all the assets of the firm are owned by another agent, his first order condition is:

$$1/2\ v^1(a_1, a_{F1},a_{F2},a_{F3}) = c_1'(x_1) \qquad (10)$$

The first order conditions for each of the other agents will be symmetrical.

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[9] It might be worth explicitly deriving the Shapley value in the three agent case. Agent 1 can be in four coalitions: {1,2,3}, {1,2}, {1,3} and {1}. The probability p(S) of being in each is 1/3,1/6,1/6 and 1/3, respectively.

The ownership structure that provides the greatest incentives to an agent can be determined by comparing the left hand sides of the two equations. If the assets are highly or strictly complementary, then the second, third and fourth terms of the first equation will be low or zero. In this case, dividing the assets will provide lower incentives than keeping them together, even for an agent who is not the owner of the united assets. On the other hand, if the information a_1 applies mainly to the physical asset a_{F1}, and they are fairly productive even when separated from a_{F2} and a_{F3}, then the first equation shows that separate ownership provides close to the first best incentives for the agent.[10]

The fact that there are several agents, each of whom has an important information asset, a_i, that requires access to the physical assets of the firm to be productive means that first-best efficiency cannot be achieved by organizing as a single firm, as shown in equation 10. Therefore, where information technology results in a decentralizing of information, it opens the door to a parallel effect of decentralization of asset ownership, that is in an increased use of markets to coordinate economic activity.

Moreover, the preceding discussion also highlights the importance of the asset specificity of the physical assets in the integration/non-integration trade-off. If information technology makes assets more flexible, so that they are not as locked-in to other particular assets, then it will facilitate the decentralization of asset ownership. This is essentially the argument of Malone and colleagues (Brynjolfsson, Malone & Gurbaxani, 1988; Malone, Yates & Benjamin, 1987), among others. On the other hand, when the technology increases lock-in, for instance because of network externalities, proprietary standards or idiosyncratic hardware and software protocols, it will make decentralization more costly.

Thus, technology will affect the organizational choices of the firm both through its impact on the distribution of information and by changing the nature of the non-human assets. These effects interact with each other and feedback on themselves. The best incentives can be achieved either 1) through the centralization of information and asset ownership in one party, in which case there is no cost to high asset specificity, or 2)

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[10] In dynamic contexts, a third option may be optimal: sequential control over time, depending on which agent had the greatest need for the assets at an given time. This was the approach favored by the three mythological Graiae who rotated possession of a single eye and tooth, and may also be an apt model for the "ad-hocracies" and "cluster organizations" (Eccles, 1988; Toffler, 1982; Mills, 1990) identified in more recent lore. Of course, the effectiveness of this approach is predicated on clear criteria for when different individuals or coalitions may take over control of the assets.

through decentralization of information and assets, which requires low asset specificity. Thus, one would expect to see trends affecting the distribution of information influence the types of physical assets used in production, and vice versa.

3.4 How does "coordination information" affect the distribution and ownership of production assets?

Up until now, we have only considered complementarities among the physical assets or between information and physical assets, not among the information assets themselves. Obviously, when there are multiple informed agents working closely together, each of them may need access to the information possessed by some other agent at any given time. Such interactions can become exceedingly complex, leading to combinatorial explosion and making explicit contracts unworkable (Mailath & Postlewaite, 1989; Rosen, 1988). What's worse, if every agent truly depends on information known only to other agents, then no rearrangement of the physical assets alone can eliminate this interdependency. There will always be insufficient incentives comparable to those of when complementary physical assets are owned by separate agents (e.g. equation 9).

However, one way to reduce the number of necessary links between agents is to channel all interactions through a central "coordinator"[11] (Malone & Smith, 1988). The existence of one agent who has coordination information that is necessary to make each of the other agent's information productive has interesting implications for the distribution of physical assets. In particular, it can make centralized ownership of all physical assets optimal if either 1) it is important to provide incentives to the "coordinator" or 2) the physical assets are even weakly complementary.

To analyze this case, consider the following stylized model of centralized coordination. Instead of each agent being able to contact the other agents directly, assume that they can only communicate with a central "coordinator".[12] Because of his positioning, the central coordinator obtains information that is essential to the productivity of the agents.[13] This set-up reduces the total number of links that need to be maintained, but also

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[11] Interestingly, this is also the principle that enables Federal Express and other hub-and-spoke operations to economize on their air routes.

[12] Equivalently, suppose that direct communication is allowed but is prohibitively expensive because it would require that each of the n agents maintain a database of n-1 addresses for the other agents, instead of just one address: the central coordinator's.

[13] Of course, the coordinator, in his role as entrepreneur may also have some prior information, skills or assets that his positioning merely serves to augment.

make the agents very dependent on the central coordinator. Formally, assume that the typical agent needs access to the coordination information, a_c, to be productive, but that the information of any given agent is not essential to the coordinator or the other agents directly. Assume further that the productivity of any agent is enhanced the more physical assets, a_{Fi}, to which he has access.

When each of the agents owns some physical assets (and his information, a_i), the first order condition for a typical agent is:[14]

$$1/2\ v^i(a_i, a_{Fi}, a_c) + 1/2\ v^i(a_i, a_{Fi}) = c_i'(x_i)$$

When the central coordinator owns all the physical assets, then agent i's first order condition is:

$$1/2\ v^i(a_i, a_{Fi}, a_c) + 1/2\ v^i(a_i) = c_i'(x_i)$$

Because the agent needs access to the coordination information, the second term in each equation is equal to zero, so the incentives for a typical agent do not change under alternative ownership structures. However, the incentives for the coordinator are unambiguously improved by giving the coordinator ownership of all the physical assets. Thus, if it is important to provide incentives to the central coordinator, centralized ownership is optimal.

Interestingly, shifting ownership of non-human assets from one agent to the coordinator may also enhance the incentives of the *other* agents, making it optimal even in the absence of the beneficial effect on the coordinator's incentives. This will be the case when the physical assets are at least weakly complementary. For tractability, consider the case of just two agents (i = 1,2) and a coordinator (c) in which the two agents each owns a physical asset, a_{Fi}, that is weakly complementary with the other's, and each has some valuable information, a_i. Then each agent's first order condition is given by:

$$1/3v^i(a_i, a_{Fi}, a_{Fj}, a_c) + 1/6v^i(a_i, a_{Fi}, a_c) + 1/6v^i(a_i, a_{Fi}, a_{Fj}) + 1/3v^i(a_i, a_{Fi}) = c_i'(x_i),$$

for i = 1,2, and $j \neq i$.

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[14] The marginal product of agent i is assumed to be unaffected by the physical or information assets specific to other agents, so we need only consider coalitions with and without the central coordinator.

Alternatively, if both the physical assets of the firm are owned by the central coordinator, each agent's first order condition is:

$$1/2\ v^i(a_i, a_{Fi}, a_{Fj}, a_C) = c_i'(x_i)$$

Under the assumption that each agent needs access to the central coordinator's information to be productive, the third and fourth terms of the first equation are zero. If the physical assets a_{Fi} and a_{Fj} are even weakly complementary, then the two remaining terms will sum to less than $1/2\ v^i(a_i, a_{Fi}, a_{Fj}, a_C)$, but this is precisely the incentive that the agent would get under centralized asset ownership. Thus when there is a need for centralized coordination, all agents' incentives are improved by having ownership of assets also centralized. In other words, *centralized coordination is more efficiently carried out in firms than in markets*. Conversely, if coordination directly between the agents becomes feasible, then the need for centralized coordination and centralized asset ownership is diminished.

The idea of thinking of the firm primarily in terms of its coordination function has received much attention (Mailath & Postlewaite, 1989; Malone, 1987; Rosen, 1988; Winter, 1988) but it has been difficult to derive the link between coordination structures and asset ownership. Treating information, and particularly coordination information, as an asset and employing the property rights approach may be a beginning for such a theory, but clearly much work still needs to be done to understand and formalize the concept of coordination information as an "asset".

4. Conclusion

4.1 Summary

There have been significant changes in the way economic activity has been organized since the inception of large scale investment in information technologies like computers. Researchers have found both empirical and theoretical support for a relationship between these two phenomena. In this paper, I add to this research by showing how agency theory, and particularly the property-rights approach to the nature of the firm, can provide insight into the mechanisms by which information technology influences organizational structure.

The models indicate that information technology will result in reduced integration and smaller firms to the extent that it:

1) leads to better informed workers, who need incentives,

2) enables more flexibility and less lock-in in the use of physical assets, and

3) allows direct coordination among agents, reducing the need for centralized coordination.

On the other hand, the framework suggests that more integration will result from information technology where:

1) network externalities or informational economies of scale support the centralized ownership of assets and

2) it facilitates the monitoring, and thus contractibility, of agent's actions.

More than one of these phenomena may be important in any given case.

4.2 Comparison with empirical evidence

There has only recently been broad scale econometric analysis showing that information technology is in fact broadly correlated with significant reductions in vertical integration and firms size (Brynjolfsson, Malone, Gurbaxani & Kambil, 1991a). While one can infer from this that one or more of the first three mechanisms discussed above is especially relevant empirically, the framework introduced in this paper provides a basis for more specific hypothesis testing. For instance, where the technology has eliminated routine jobs while augmenting the demand for workers with more education, the framework predicts a decline in firm size, ceteris paribus. Because information technology has been found to be broadly correlated with increased demand for more educated workers relative to less educated workers, the framework suggests that this may be a mechanism by which information technology leads to a general decline in firm size.[15]

At the same time, by highlighting the link between *uncontractible* actions and the use of ownership to provide incentives, the framework can also help explain cases in the other direction. One example is that partnerships such as law firms have traditionally been fairly small compared to corporations, which is consistent with the conclusions in section

[15] Interestingly, even after controlling for observable education and skill levels, workers that work with computers were found to earn an additional wage premium of 10 to 15 percent [Krueger, 1991 #422].

3.2. However, in the 1980s some law firms grew to over 200 partners (Labaton, 1990), which would seem to be beyond the size consistent with equation 8. One explanation is that these firms can more accurately apportion revenues and costs through explicit contracts by using computers to track billing and asset use on an individual basis. In this sense, the uncontractible "community property" is minimized and the partnership functions more like a conglomerate of individual entrepreneurs, each with his or her own "turf". The growing numbers of non-equity "partners" (Aoki, Gustafsson and Williamson, 1990) is also consistent with the idea that control of non-human assets is no longer of such central importance in large law firms because uncontractible contingencies have been reduced.

It should also be possible to examine other predictions of the framework. For instance, the network externalities and economies of scale inherent in ATM's and large databases, respectively, should lead to increased integration in the banking industry. Increased flexibility of physical assets, like robots, should make it possible to decouple some manufacturing plants from one another. Where technology reduces the need for centralized coordination, it should also be associated with the more decentralized asset ownership, as in value-adding partnerships and markets coordinated through interorganizational information systems.

4.3 Comparison with related literature

The findings of this paper are broadly consistent with three related strains of literature, but also build on their conclusions. Below, I compare the results of this paper with previous applications of 1) transaction costs literature, 2) coordination theory, and 3) the Grossman-Hart-Moore approach to property rights.

4.3.1 Transaction costs

The transaction costs literature pioneered by Williamson (1985) has been invoked to explain the recent shift from hierarchies to markets (Brynjolfsson, Malone & Gurbaxani, 1988; Kambil, 1988; Malone, Yates & Benjamin, 1987). The basic result of this literature, that as information technology reduces asset specificity it facilitates de-integration, is supported and formalized in a model presented in this paper. However, a second aspect of the Williamsonian credo is not supported. The transaction cost approach posits that market failure leads to increased integration and that markets break down when it is difficult to write complete contracts (because of bounded rationality combined with complexity and

uncertainty, according to Williamson). This suggests that the shift to markets associated with the introduction of information technology is a signal of an increased ability of firms to write complete, contingent contracts with agents.[16] Unfortunately, field studies indicate that top management in the most organizations of the 1980s have actually been writing *less* detailed contracts with employees and suppliers than in earlier eras (Kanter, 1989b; Peters, 1988; Piore, 1989). The increased knowledge and flexibility of agents and the increasingly volatile environment has apparently outstripped any improvements in management's bounded rationality.

Although one could argue that, even if this is true, transaction costs are still reduced on balance because of the increased flexibility of assets discussed above, the analysis presented in section 3.2 suggests an alternative explanation. The extent to which an agent's actions are contractible does not by itself determine organizational structure, rather it is the interaction of contractibility with the need to provide incentives via asset ownership that defines the costs and benefits of market coordination. In fact, it is precisely the party whose actions are least contractible who is most in need of asset ownership to provide, and make credible, the right incentives. Thus, if information technology has lead to more decentralized asset ownership by affecting contractibility, it is either by reducing the contractibility of the agent's actions, or increasing the contractibility of the principal's actions. Either of these effects would make it more important to provide agents with asset ownership, which means using market coordination. In contrast to the transaction cost approach, this analysis indicates that a technology that leads to general increase in contractibility will not by itself lead to increased use of markets. Indeed, if complete, contingent contracts could be written for all actions, there would be no "residual" rights and thus ownership and the concept of "firms" vs. "markets" would be meaningless.

4.3.2 Coordination theory

Malone and his colleagues (Malone, 1987; Malone, 1988; Malone & Smith, 1988) have pioneered a theory of coordination that formally distinguishes organizations by their costs of coordination, production, and vulnerability. A basic result of this literature is that centralized structures can economize on the costs of coordination, at the expense of production and vulnerability costs. Malone and Smith (1988) argue that many of the historical changes in the dominant organizational structures of the economy, as catalogued

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[16] This hypothesis is consistent with the familiar conception that computers are best modelled as tools to slacken the constraints of bounded rationality.

by (Chandler, 1977), can be explained by changes in technology and the environment that increased the relative importance of economizing on coordination costs. They also suggest that less centralized coordination mechanisms will come to dominate as information technology reduces coordination costs and speculate that this will reverse the historical trend toward larger firms.

While their models show that centralized coordination can theoretically take place either within firms or through brokered markets, the model presented in section 3.5 provides a way of distinguishing the circumstances under which each ownership structure will dominate. Indeed, it suggests that in the presence of incomplete contracts, most centralized coordination will optimally take place within firms (that is, under centralized asset ownership). Only when 1) the central coordinator's job is well-defined enough that he can be provided with incentives through a relatively complete contract, and 2) the goods and services being coordinated are not too complementary, will markets (distributed asset ownership) be optimal. These conditions seem likely to hold for financial brokers and commodities trading, but are less descriptive of CEOs or manufacturing activities. The approach taken in this paper formally links centralized coordination in the latter sorts of cases with firms, and is thus is a natural extension of earlier work in coordination theory.[17]

4.3.3 The Grossman-Hart-Moore approach to property rights

Finally, the Grossman-Hart-Moore property rights approach to identifying the determinants of integration and organizational structure has enjoyed increasing success and recognition from theoreticians, and was obviously central to the analysis presented in this paper. This theory exposes the role of non-human assets in affecting the incentives of agents, but does not presume to explain from whence the need for incentives arises. While it shows the importance of giving ownership of essential assets to the those agents that have important non-contractible actions, the theory by itself is not sufficient to enable predictions about whether information technology would be expected to lead to greater use of firms or markets. For instance, (Piore, 1989) considered applying the property rights framework, and although he found it provided some valuable insights, he concluded:

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[17] The theories of Malone and colleagues abstract from incentive considerations, in the spirit of team theory. Introducing incentives provides a mechanism through which asset ownership can affect coordination. However, incentives are not sufficient for this link. Rosen (1988), and Mailath and Postlewaite (1989) argue that coordination problems can make incentive contracts difficult to write among large numbers of agents and show that centralization will be often be cheaper, but they do not formally tie centralized coordination to centralized asset ownership (firms).

> The ability of this model to assimilate the recent corporate changes [is] more limited than it appears. The critical outcomes ultimately depend in the model upon the location of the information required to make decisions which are expensive to anticipate, and the model itself does not tell you where that information is located. For that one must ultimately turn to a production (or technologically) based theory.

By showing how information technology can, and has, lead to a broader distribution of information in many organizations and how this has affected the need for incentives, the analysis in this paper and a previous paper [Brynjolfsson, 1990b #26], takes some steps towards addressing this prerequisite to applying the property rights based approach. While there is no technological inevitability in these models, it is hoped that they do address Piore's call by clarifying the mechanisms by which the changes in technology can lead to commensurate changes in the dominant organization forms in the economy.

The property rights framework of Grossman, Hart and Moore highlights the central role of non-human assets because they can be bought and sold as well as "owned". In this paper, I have treated human assets, specifically the productive knowledge or information of the agents, on an equal footing. The more explicit modelling of the "information asset" facilitates the analysis of organizations in which control of information, not physical assets, is determinative.

The residual rights of control over who has access to the productive information in an agent's brain may often be more important than the residual rights associated with non-human assets which he owns. For instance, the departure of a key knowledge worker (and his knowledge) may affect the other members of the firm more than the loss of the lease to their building, or even of their office equipment.[18] Instead of modeling only the alienable assets, I include inalienable assets as well, but add the constraint that asset allocations which separate inalienable[19] assets from their original "owners" are not feasible.

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[18] Grossman and Hart (1986) formally recognize this possibility when they remark that a subvector of residual rights may always remain under the control of manager j even after firm j is sold to someone else, but it plays no role in their subsequent analysis. More colorfully, Robert Reich [, 1990 #379] has argued that Americans shouldn't be concerned that Bruce "born-in-the-USA" Springsteen now works for the Japanese (his record label has been purchased by Sony) because Springsteen still controls his own human capital.

[19] Actually, the definition of which assets are inalienable is changing with technological advances. For instance, to the extent that expertise can be embodied and delivered in the form of a knowledge-based expert system, it may be entirely alienable. Books, lectures and other vehicles for purchasing know-how have existed even longer. A natural extension of this paper would be to examine the organizational effects of making expertise alienable through software in areas like tax law or medicine.

This approach may prove useful as the ranks of knowledge workers and service workers grow, increasing the need to model how incentives and organizational structure are affected by the distribution of the residual rights associated with both human and non-human assets. For instance, one immediate implication of the inalienability of human assets is that, unlike complementary physical assets, complementary human assets cannot be centralized under the ownership of a single agent. This suggest that incentive problems will be particularly severe in large, knowledge-intensive enterprises.[20]

Happily, in most cases, the productivity of one agent's information does not depend entirely on its synergies with the information or physical assets controlled by other specific individuals. In fact, when the information possessed by agents is not idiosyncratic, an arrangement with close to optimum incentives can be achieved: distributed, independently owned assets, giving each agent claim to the non-contractible, residual income generated by his actions. In this paper, I have shown that this explanation may be consistent with the economy-wide growth of small firms and decline in vertical integration. As information work has come to account for a dominant share of labor costs, providing sufficient incentives for information workers becomes increasingly important. In the absence of contractibility, ownership may be only way of providing such incentives.

At times, the recent restructuring of firms and industries appears to have been as indiscriminate as it has been dramatic, underscoring the need for better theory. Although models of how firms and markets coordinate agents have progressed as much in the past ten years as they did in the previous fifty, glaring gaps remain. Fortunately, the opportunities for sharp, empirical tests enabled by the recent changes in both the technology and superstructure of economic organization give every reason to be optimistic about future advances in our understanding.

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[20] If complete contracts cannot be written, possible organizational responses to mitigate the potential for opportunism include increased use of repetition and reputation to encourage the development of trust among agents, (see Kreps, 1984 within the firm; Sabel, Kern and Herrigel, 1989, among firms); hierarchical decomposition of the tasks, to minimize interdependencies; and improved goal alignment, for instance by encouraging "company spirit", or the development of anti-opportunistic ethics. Ultimately, the intrinsic appeal of the task may prove to be more important than any scheme that affects only its extrinsic costs and benefits.

Appendix. Assumptions underlying the property rights framework

Most of these assumptions are fairly natural, but it is worth noting that assumption A4 says that the actions of the agents are complementary at the margin and assumption A6 says that marginal return on investment is not decreasing with the number of other agents and actions in the coalition. See (Hart & Moore, 1990) and (Grossman & Hart, 1986) for a detailed discussion of all the assumptions.

There is a set S of I risk neutral agents each of whom takes a scalar action x_i that affects his value in some uncontractible way and that costs him $c_i(x_i)$. Each agent chooses his action non-cooperatively, generating a total value $v(S,A|x)$ that will be divided among the agents. The subset of assets A is controlled by the subset S of the agents according to a mapping $\alpha(S)$ satisfying B1-B3.

B1: $\alpha(S) \cap \alpha(\underline{S}\backslash S) = \emptyset,,$ where $\emptyset$ is the empty set.

B2: For all subsets $S' \subseteq S$,

$\alpha(S') \subseteq \alpha(S)$

B3: $\alpha(\emptyset) = \emptyset$.

In addition, the model makes the following assumptions.

Assumption A1:

$c_i(x_i) \geq 0$ and $c_i(0) = 0$

c_i is twice differentiable

$x_i \in [0,X_i]$

if $X_i>0$, then $c_i'(x_i)>0$ and $c_i''(x_i)>0$ for $x_i \in (0,X_i)$

with $\lim_{x_i \to 0} c_i'(x_i) = 0$, and $\lim_{x_i \to X_i} c_i'(x_i) = \infty$.

Assumption A2:

$v(S,A|x) \geq 0$ and $v(\emptyset,A|x) = 0$

$v(S,A|x)$ is twice differentiable in x.

If $X_i > 0$, then $v^i(S,A|x) \geq 0$ for $x_i \in (0,X_i)$.

$v(S,A|x)$ is concave in x.

Assumption A3:

$$v^i(S,A|x) = 0, \text{ if } i \notin S.$$

Assumption A4:

$$\frac{\partial}{\partial x_j} v^i(S,A|x) \geq 0, \text{ for all } j \neq i$$

Assumption A5:

For all subsets $S' \subseteq S$, $A' \subseteq A$,

$$v(S,A|x) \geq v(S',A'|x) + v(S\backslash S',A\backslash A'|x).$$

Assumption A6:

For all subsets $S' \subseteq S$, $A' \subseteq A$,

$$v^i(S,A|x) \geq v^i(S',A'|x).$$

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