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MANUSCRIPT

Distributed knowledge and the organization of economic activity

Vipin P. Veetil[1]

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Abstract

This paper develops a simple simulation model to study the relation between the nature of knowledge and the architecture of economic systems. The market and the firm are different mechanisms for coordinating economic activity in a system where knowledge is widely dispersed. While the market solves coordination problems by decentralizing decision-making, the firm solves coordination problems by centralizing knowledge. The market incurs the cost of finding potential exchange partners and agreeing on terms of trade, while the firm incurs the cost of centralizing dispersed knowledge. The market therefore has an advantage over the firm in coordinating activities in which knowledge is difficult to centralize. The nature of knowledge involved in an economic activity influences not only the choice of the institution through which it is coordinated but also the internal structure of the institution. More specifically, the more hierarchical the firm, the better it is at using changing knowledge, but the worse it is at using knowledge which is difficult to transfer from one individual to another. Therefore, the number of layers in the hierarchy of the firm is influenced by the rate at which knowledge changes relative to the difficulty associated with communicating it.

Keywords Market · Firm · Hierarchy · Institutions · Dynamic knowledge · Tacit knowledge · Simulation model

JEL Classification D21 · D22 · L11 · L22 · P10

✉ Vipin P. Veetil
vipin.veetil@gmail.com

[1] Department of Humanities and Social Sciences, Indian Institute of Technology Madras, Chennai 600036, India

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1 Introduction

Much of the literature on firm theory uses opportunistic behavior to explain the division of economic activity between firms and markets, while the literature on organization theory uses information and cognitive considerations to explain the internal structure of firms. Theories which explain the internal structure of firms have little to say about the division of economic activity between firms and markets, and those which explain the boundary of the firm shed little light on its internal structure. This state of affairs is somewhat perplexing. It appears unlikely that the factors which influence the institutional choice of economic coordination do not influence the internal structure of the institutions. We develop a theory in which the architecture of the economic system—markets, firms, and the internal organization of firms—is shaped by how it uses dispersed knowledge. Our theory is built on Coase's (1937) insight on the cost of decentralized coordination and Hayek's (1945) work on the cost of centralized coordination.[1]

A basic economic problem is how to coordinate activities in a system where knowledge is widely dispersed. Markets and firms are different mechanisms for using widely dispersed knowledge. In an idealized market, decision rights are vested in individuals who possess bits and pieces of knowledge, and coordination happens through decentralized exchange between autonomous agents. In an idealized firm, the entrepreneur-coordinator possesses decision rights to coordinate the activities of different individuals within the firm. The firm must however bring knowledge dispersed among many individuals to the disposal of the entrepreneur-coordinator to use that knowledge for coordination. Both the market and the firm solve the problem of aligning decision rights with knowledge necessary to make decisions. While the market solves the problem by decentralizing decision-making, the firm solves the problem by centralizing knowledge.

The above line of reasoning naturally leads one to the proposition that the market is superior to the firm in circumstances where the cost of decentralizing decision-making is lower than the cost of centralizing knowledge. The question then is what determines these costs? Coase (1937) shed light on the cost of decentralizing decision-making. He argued that the market process involves the cost of finding potential exchange partners and agreeing on terms of trade. Resources are used to search for trading partners and negotiate the terms of trade. We refer to these as the "costs of exchange". The firm does not have to incur costs of exchange because the entrepreneur-coordinator, not decentralized exchange, creates coordination. Put differently, within the firm, workers do not search for others workers with whom to exchange or negotiate terms of trade.

[1] As Langlois (2013, p. 248) put it, though Hayek was writing in the context of the socialist calculation debate, Coase and Hayek "really are addressing the same problem: what are the limits of the market and of the firm". In a similar vein, Foss and Klein (2014, p. 472) argue that "the Hayekian challenge to planning applies to firms as well as to centrally planned economies, and raises fundamental issues that are still not resolved in organisation theory relating to the use of authority, planning, and direction in the presence of dispersed knowledge".

So much for the cost of using the market mechanism. But what determines the cost of using the firm? After all, though the firm does not incur costs of exchange, it must incur some other cost of organizing economic activity. This is simply because if the firm is always less costly than the market, then a single firm would organize the entire economy. Which is something we do not observe in real world economic systems.

Unfortunately, Coase did not say much about of the origins of the cost of organizing economic activities through the firm.[2] We do, however, find an answer to the question of the cost of centralizing knowledge within Hayek's work on rational economic calculation. Hayek (1945) argued that the principle cost of centralized coordination originates from the coordinator having to make decisions with imperfect knowledge simply because dispersed knowledge cannot be perfectly centralized. Hayek presented two reasons for why dispersed knowledge cannot be perfectly centralized. First, knowledge is dynamic, it changes with time.[3] Some of the knowledge of economic significance is the knowledge of particular circumstances of time and place. In so far as it takes time to transfer knowledge up a hierarchy, some of the knowledge that reaches the central coordinator is dated and incorrect, and so are the plans made using the knowledge. The second reason for why distributed knowledge cannot be perfectly centralized is that knowledge has a tacit dimension. Some of it is lost in going from one agent to another simply because not all of it can be codified. Agents may know how to do something without necessarily being able to articulate, ratiocinate, or communicate what they know. To use Ryle's (1945) words, much of the knowledge of economic relevance is "knowing how" rather than "knowing that". Often this "know how" is developed in a particular context, outside of which the knowledge either does not exist or cannot be used. It may be possible to transfer some of this knowledge to others, nonetheless not all of it can be accurately conveyed to another individual.[4]

Suppose distributed knowledge can be more or less tacit and more or less dynamic. In such a world, Hayek's thesis would imply that the greater the dynamism

[2] Coase (1937) did not say much about the origin of cost of the firm. Coase (1988, p. 40, italics ours) recalling his seminal article says: "Of course, organizing a firm would be profitable only if the costs avoided were greater than the costs that would be incurred by the firm in coordinating the activities of the factors of production. *I did not attempt to uncover the factors that would determine when this would be so*".

[3] In Hayek's (1945, p. 522) words: "To know of and put to use a machine not fully employed, or somebody's skill which could be better utilized, or to be aware of a surplus stock which can be drawn upon during an interruption of supplies, is socially quite as useful as the knowledge of better alternative techniques. And the shipper who earns his living from using otherwise empty or half-filled journeys of tramp-steamers, or the estate agent whose whole knowledge is almost exclusively one of temporary opportunities, or the arbitrageur who gains from local differences of commodity prices, are all performing eminently useful functions based on special knowledge of circumstances of the fleeting moment not known to others."

[4] Polanyi (2009) describes a psychological experiment where participants were given an electric shock whenever they uttered associations of certain words. The participants learned to forestall shocks by avoiding utterances of certain associations. However, they were not able to articulate what they were doing. They had learned to avoid shocks, but the knowledge of how to do so was functional and relational. The knowledge did not exist detached from the context in which it was learned.

and tacitness of knowledge, the lower the accuracy of knowledge made available to the entrepreneur-coordinator in the firm, and the less coordinated the plans made using the knowledge. The cost of the firm—about which Coase was so elusive—therefore is the output lost because of imperfectly coordinated plans, which themselves are a consequence of imperfect knowledge made available to the entrepreneur-coordinator.

All this means that the relative cost of the market and the firm depends on the nature of knowledge. The cost of exchange does not increase with the dynamism and tacitness of knowledge while the cost of firm-coordination does. Therefore, the greater the dynamism and tacitness of knowledge, the greater the cost of the firm relative to the market.[5] As to whether an activity must be organized through the firm or the market therefore depends on the nature of knowledge involved in that activity.

The problem of using dispersed knowledge not only influences the division of economic activities between the market and the firm, but also the internal organization of the firm. More specifically, the levels of hierarchy within the firm is determined by the relation between the dynamism and tacitness of knowledge. While hierarchy decreases the problem of centralizing dynamic knowledge, it aggravates the problem of centralizing tacit knowledge. Hierarchy decreases the problem of centralizing dynamic knowledge because the entrepreneur-coordinator is able to collect knowledge within a shorter period of time by relying on subordinates, rather than meeting all ground-level agents. Hierarchy aggravates the problem of centralizing tacit knowledge because ground-level knowledge must pass through more individuals to reach the entrepreneur-coordinator. And some of the knowledge is lost at each point of transfer.

In short, the nature of knowledge involved in an economic activity influences not only the choice of the institution through which it is coordinated but also the internal structure of the institution. Activities with highly dynamic and highly tacit knowledge are likely to be organized through the market, while those with less dynamic and less tacit knowledge are likely to be organized through the firm. Among the activities organized through the firm, the hierarchical structure within the firm is influenced by the degree of dynamism of knowledge relative to the degree of tacitness of knowledge. Where the problem of dynamism is more pronounced than the problem of tacitness, one is likely to find more hierarchical firms.

We formalize the relation between the nature of knowledge and the architecture of economic systems using a simple simulation model. More specifically, we develop a system in which workers are endowed with some quantity of an input. The initial distribution of the input is inoptimal, i.e. total output can be increased by a reallocation of the input. Each worker is aware of his quantity of input but not the social distribution. This private knowledge can be used through the market or the firm mechanism. The tacitness of knowledge is modelled as the probabilistic failure

[5] Our formal model will show that the market too suffers from an increase in the tacitness and dynamism of knowledge, but less so than the firm. This is because the redundancy associated with the massively parallel process of interactions within the market allows it to considerably overcome the problems associated with using dynamic and tacit knowledge.

of workers to communicate their private knowledge to potential traders in the market or to managers within the firm. The dynamism of knowledge is modelled via periodic changes in the distribution of inputs among workers, which is equivalent to a change in their private knowledge. We simulate the use of knowledge within an idealized market and two idealized firms, a tall firm and a short firm. More specifically, we use the Monte Carlo method to characterize the relative performance of the three systems with variation in parametric values of dynamism and tacitness of knowledge. Our simulation results are consistent with our conceptual intuition about the role of knowledge transfer in shaping economic organization.

The rest of our paper is organized as follows. Section 2 presents a simple model to pin down the transmission of distributed knowledge under alternate arrangements of coordinating economic activity. Section 3 presents results from model simulation. Section 4 offers concluding thoughts. Appendix 1 discusses the relation between the ideas developed in this paper and the ideas that guide other knowledge-based theories of economic organization.

2 The model

A population of workers produces output using a single input. Each worker produces output q with a single input x using the production function $q = e^{-|x|}$, where $|x|$ denotes the absolute value of x. The production function implies output is maximum when $x = 0$. Each worker begins with a random initial endowment of x from a uniform distribution. Some workers begin with negative quantities and others with positive quantities of x. The quantity index of the input x is arbitrary. One may think of the workers as cooks and the input as salt, where too much and too little of it is undesirable.[6] The market and the firm are different institutional mechanisms to reallocate the input among workers to produce maximum output. In the market, workers meet in pairs and exhaust gains from trade. In the firm, the entrepreneur-coordinator centralizes knowledge about the distribution of the input and then redistributes the input among workers.

Knowledge about the input is private, dynamic, and tacit in the market and in the firm. Knowledge is private because each worker knows his input quantity but the knowledge of the distribution of the input among all workers is not given to anyone. Knowledge is dynamic because at each time step some proportion $d \in (0, 1)$ of workers experience idiosyncratic shocks to their input. The parameter d denotes the dynamism of knowledge. The input of a worker who experiences an idiosyncratic shock is incremented or decremented by a random quantity drawn from a uniform distribution. The distribution of input, and therefore

[6] Negative and positive values of the inputs are merely a means to set up a coordination problem, i.e. the problem of reallocation of inputs so as to maximize output. It makes no difference if the support of the distribution is shifted to strictly positive or strictly negative values with a concomitant change in the production function itself. An earlier version of the model worked with each worker possessing two goods. In that setting they began with an inoptimal combination of the two inputs. The model was simplified to a system with a single good because one good proved sufficient to depict a coordination problem.

the private knowledge about the input, changes with time. Knowledge is tacit because each worker fails to communicate knowledge of his input quantity with probability $t \in (0, 1)$. The parameter t denotes the tacitness of knowledge. Workers fail to communicate in the market and the firm. Furthermore, the managers in the firm too fail to communicate knowledge to higher level managers with probability t.

2.1 The market

The market is a process of bilateral exchange. Each time step, each worker is randomly matched with another worker. Each pair of workers exhaust gains from trade. For instance, when worker W_0 with 8 units of input meets worker W_1 with -10 units of input, they trade up to the point where W_0 has 0 units and W_1 has -2. In a population of W workers, at each time step there are $W/2$ parallel bilateral matches. Since knowledge is dynamic, at each time step, d proportion of workers experience an increases or decrease in their input. Since knowledge is tacit, when two workers meet, with probability t each worker fails to communicate the knowledge of her inputs to the other worker. No trade occurs if either worker fails to communicate. No trade occurs between two workers when both have either positive or negative units of the endowment. Trades are limited to Pareto improving transactions.

2.2 The firm

The firm is a symmetric hierarchical tree with ranked nodes. The workers have rank 0, a manager's rank indicates his level, the entrepreneur-coordinator has the highest rank denoted by r. Let k denote the number of subordinates of a manager. Suppose the firm is like the one depicted in Fig. 1. The nodes labelled W are workers and those labelled M are managers. Each superscript indicates the rank of a node. M_0^2 is the entrepreneur-coordinator. Managers meet workers to collect knowledge of their input quantities. In the first time step, M_0^1 meets W_0^0 and M_1^1 meets W_2^0. In the second time step, M_0^1 meets W_0^1 and M_1^1 meets W_3^0. At the end of the second time step, knowledge about the distribution of the input among the four workers is available to the two managers of rank 1 (M_0^1 and M_1^1). In the third time step, M_0^2 meets M_0^1. In the fourth time step, M_0^2 meets M_1^1. At the end of the fourth time step, knowledge about the distribution of the input among the four workers is available to the entrepreneur-coordinator. Using the knowledge collected, the entrepreneur-coordinator reallocates inputs among workers with the goal of maximizing output. The entrepreneur-coordinator (M_0^2) does not change the allocation of resource among workers about whom he receives no knowledge. Put differently, if the knowledge about a worker is not transferred to the entrepreneur-coordinator, because of the failure to transmit it from one level to another, the resource allocation of the worker remains unchanged.

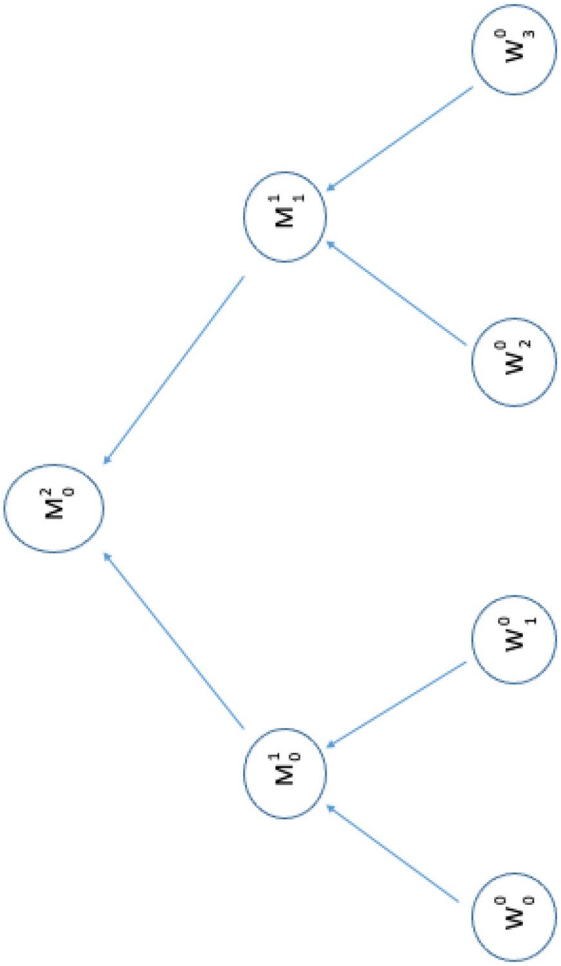

Fig. 1 Structure of a sample firm with four workers

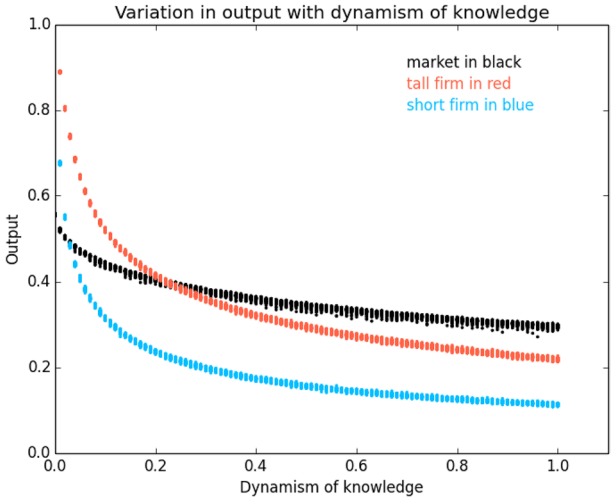

Fig. 2 The figure plots 100 simulated values of output for each institution for each value of dynamism in the range [0, 1] with increments of 0.01. Tacitness of knowledge is set to 0

2.3 Model simulation

We compare the output of a synthetic market and two synthetic firms (a tall firm and a short firm), each with a population of 10, 000 workers. The tall firm has four layers of hierarchy ($r = 4$) and each manager has ten subordinates ($k = 10$). The short firm has two layers of hierarchy ($r = 2$) and each manager has one hundred subordinates ($k = 100$). The output of the firms is measured after the entrepreneur-coordinator collects knowledge and reallocates the input. The output of the market is measured at the hundredth time step.[7] The market cost of finding potential exchange partners and agreeing on terms of trade is fixed at forty percent of output, as suggested by Wallis and North's (1986) estimate. Parameter m of the $uniform(-m, m)$ distribution determines the random initial endowment of input. m is fixed at 1000. Parameter n of the $uniform(-n, n)$ distribution determines gains and loses in units of input due to idiosyncratic shocks. When knowledge is dynamic, n is fixed at unity. The model is written in Python programming language. The model code is available at: https://www.bitbucket.org/VipinVeetil/knowledge_firm_market.

In the next section, we compare the output of the market and the firms as the dynamism $d \in (0, 1)$ and tacitness $t \in (0, 1)$ of knowledge vary. Figures 2 and 3 plot output as a proportion of maximum potential output (output normalized by dividing it by maximum potential output). Maximum potential output is the total output when each agent has an optimal quantity of input.[8] The cost of the institutions is the

[7] The market takes several time steps to converge to its asymptotic output. By 100 time steps this convergence is near-complete (from a numerical point of view).

[8] We divide by the hypothetical maximum potential output, which is the output when the total quantity of input among all workers sums to zero. This sum may be non-zero for particular simulations as it depends on random initial allocation among workers. Nonetheless, this issue does not matter for the comparison of the system as all outputs are normalized with the same denominator.

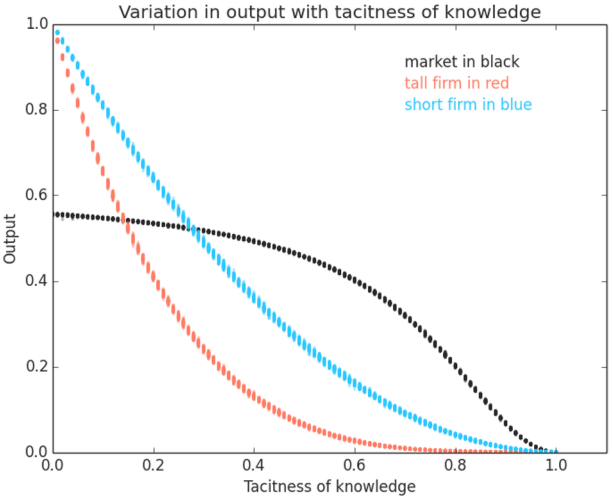

Fig. 3 The figure plots 100 simulated values of output for each institution for each value of tacitness in the range [0, 1] with increments of 0.01. Dynamism of knowledge is set to 0

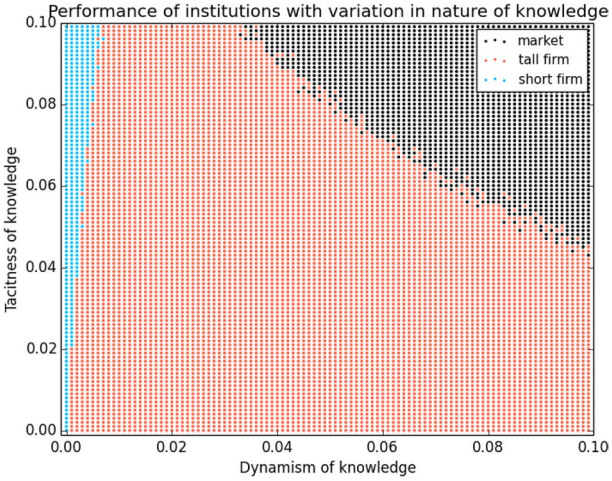

Fig. 4 The figure plots the institution that produces greatest output for different combinations of dynamism and tacitness of knowledge. The parameters of dynamism and tacitness co-range in the interval [0, 0.2] with increments of 0.001 producing a total of 40, 401 parameter combinations. Each institution is run ten times for each parameter combination. We use the mean of the ten simulations to rank the institutions

difference between output and maximum potential output; normalized cost is one minus the data points in Figs. 2 and 3. Figures 2, 3, 4 together summarize the results of more than a million model simulations.

3 The results

Result 1 *As dynamism of knowledge increases, output of the firms and the market decreases. When the dynamism is sufficiently high, the output of the market exceeds the output of the firms.*

Figure 2 plots the output of the market and the firms as dynamism of knowledge varies from 0 to 1, with tacitness of knowledge set to zero. As dynamism of knowledge increases, the output of the firms and the market decreases. The output of the firms decreases because the workers' input quantities change before knowledge about input reaches the entrepreneur-coordinator. Suppose at time step 0 a manager collects knowledge about the input quantities of workers A and B. Time passes as the knowledge travels from one manager to another up the firm hierarchy to the entrepreneur-coordinator. At time step T when the entrepreneur-coordinator receives the knowledge collected at time step 0, A and B may no longer possess the input quantities they possessed at time step 0. The entrepreneur-coordinator, acting on the basis of knowledge collected at time step 0, makes poor reallocation decisions. The greater the dynamism of knowledge, the less accurate the knowledge that reaches the entrepreneur-coordinator, the less coordinated his plans, and the lower the firm's output. The output of the market decreases with dynamism of knowledge because workers who have traded to optimal input may experience shocks that make them inoptimal. The greater the dynamism of knowledge, the greater the proportion of workers who experience shocks that make their input quantities inoptimal.

When dynamism of knowledge is low, the output of the firms is more than the output of the market. This is because the cost of finding potential exchange partners and agreeing on terms of trade overwhelms the market's superiority in using dynamic knowledge. However, when the dynamism of knowledge is sufficiently high, the market's output is more than the firms' output. The market is superior to the firms at using dynamic knowledge for the following reason. In the firms, workers have to wait for the entrepreneur-coordinator to collect knowledge and many changes in input quantities take place by the time the entrepreneur-coordinator centralizes knowledge. These changes reduce the output of the firm because the entrepreneur-coordinator reallocates the input based on dated knowledge of the distribution of input among workers. In the market, workers act on changes in their input by trading with each other and multiple trades can take place simultaneously. When knowledge changes, the market process uses new knowledge through new trades. The architecture of the market allows it to rapidly use changing knowledge because those who possess the knowledge can act upon the change in knowledge, without waiting for someone to collect it.

Result 2 *As the tacitness of knowledge increases, the output of the market and the firms decreases. When tacitness of knowledge is sufficiently high, the output of the market exceeds the output of the firms.*

Figure 3 plots output as tacitness of knowledge varies from 0 to 1, with dynamism of knowledge set to zero. As tacitness of knowledge increases, the output of the firms and the market decreases. The output of the firms decreases for the following reason. Tacit knowledge means that with probability t agents fail to communicate their knowledge of input quantities. As t increases, the knowledge that reaches the entrepreneur-coordinator decreases. The entrepreneur-coordinator cannot reallocate the input among workers about whom she has no knowledge. Therefore as t increases, the reallocation of the input and consequently the output of the firms decreases. The output of the market decreases for the following reasons. When workers meet in a market, trade happens after workers recognize gains from trade through exchanging knowledge about the input. No trade happens if either worker fails to communicate. As t increases, more workers fail to communicate, trades and reallocation of the input decreases, and consequently the output of the market decreases.

When tacitness of knowledge is low, the output of the firms is greater than the output of the market. This is because the cost of finding potential exchange partners and agreeing on terms of trade overwhelms the market's superiority over the firms in using tacit knowledge. However, as tacitness of knowledge increases beyond a point, the market's output becomes greater than the output of the firms. The market is superior to the firms in using tacit knowledge because of the following reason. In the market, if a worker fails to communicate his inputs to another worker, no trade happens. However, in the next time step the worker has another opportunity to trade with another potential exchange partner. Though she failed to communicate on the first occasion, she may succeed in communicating her knowledge on the second occasion. If the worker fails on the second occasion, she may succeed on the third occasion and so on. In the firms, if a worker fails to communicate the knowledge about his input to a manager, then the entrepreneur-coordinator does not get to know his input quantity. And even when a worker succeeds in communicating his input quantity, the knowledge may get lost on the way to the entrepreneur-coordinator if a manager fails to communicate it to another manager. (This is why the short firm outperforms the tall firm when the tacitness of knowledge is sufficiently high). The market performs better than the firms in using tacit knowledge because it has a self-corrective mechanism that the firms lack. There is a certain redundancy in the market process of massive parallel interactions that allows for past mistakes to be corrected in future interactions.

Result 3 *When knowledge is dynamic, the output of the tall firm is more than the output of the short firm. When knowledge is tacit, the output of the short firm is more than the output of the tall firm.*

When knowledge is dynamic, the output of the tall firm is more than the output of the short firm for the following reason. In the firms, each time-step, each manager collects knowledge of input bundles from one subordinate. The tall firm centralizes knowledge in forty time-steps (since $r = 4$ and $k = 10$) and the short firm centralizes knowledge in two hundred time steps (since $r = 2$, $k = 100$).

Dynamic knowledge changes with time. The more the time taken to centralize knowledge, the less the accuracy of the knowledge made available to the entrepreneur-coordinator. Since the tall firm takes less time than the short firm, the entrepreneur-coordinator in the tall firm has more accurate knowledge than the entrepreneur-coordinator in the short firm. More accurate knowledge produces better reallocation of the input among workers and therefore more output.

When knowledge is tacit, the short firm's output is more than the tall firm's output for the following reason. Tacit knowledge is probabilistically lost at every instance of communication. In the tall firm, knowledge of a worker's input is communicated four times (since $r = 4$) on the way to the entrepreneur-coordinator. In the short firm, knowledge of a worker's input is communicated two times (since $r = 2$) on the way to the entrepreneur-coordinator. The more the number of communications, the higher the cumulative probability that knowledge is lost before reaching the entrepreneur-coordinator. When knowledge is tacit, the tall firm's entrepreneur-coordinator receives less knowledge than the short firm's entrepreneur-coordinator. Less knowledge about workers means less reallocation of the input among workers and therefore less output.

Figure 4 summarizes the basic ideas of this paper by plotting the institution that produces greatest output for different values of dynamism and tacitness of knowledge. The firms produce more than the market when dynamism and tacitness of knowledge are low. The market produces more than the firms when dynamism and tacitness of knowledge are sufficiently high. The short firm outperforms the tall firm when the tacitness of knowledge is sufficiently high and the dynamism of knowledge sufficiently low.

4 Concluding thoughts

In this paper, we have argued that firms and markets are different institutions for using widely dispersed knowledge to coordinate economic activities. The nature of knowledge involved in an activity influences both the choice of the institution with which to coordinate the activity, and the internal structure of the institution. While the thesis may seem novel, it is little more than a combination of the ideas present in Hayek's (1945) "Use of Knowledge in Society" and Coase's (1937) "The Nature of the Firm". Though Hayek did not recognize the cost of decentralized exchange and Coase was silent on the origin of the cost of the firm, the two together contain the ingredients for a theory of the institutional structure of production.

Our paper is merely a first approximation of the role of knowledge in shaping the institutional structure of production. Our model compares the idealized market to the idealized firm. Some arrangements like franchises do not belong to either pure category. And most firms allow for some decentralized decision-making within themselves. One way to interpret the results of our model is to view real world institutions as complex combinations of the ideal types. Put differently, real world organizations tend to use both horizontal and vertical transmission of knowledge. The activities of workers are coordinated through managerial control *and* via distributed interactions. In this sense, one may speak of 'firmness' or 'marketness' of real world institutions.

Our analysis suggests that in areas of economic activity where knowledge is more dynamic and tacit, we are likely to see institutions with more marketness than firmness. Naturally then, the variations in the institutional arrangements will reflect the variations in the nature of knowledge across economic activities.

This empirical implication can be tested by studying the relation between measures of the marketness-firmness of various institutional arrangements on the one hand, and measures of dynamism and tacitness of knowledge in the activities that these institutions coordinate on the other. One possible measure of the 'marketness-firmness' is the extent to which an organization relies on decentralized horizontal transmission of knowledge vis-a-vis vertical transmission of knowledge. To this end one would have to develop some measure of the knowledge that is transmitted within an organization, and then map its path through the organizational hierarchy. In this process one may even discover that a given entity appears to behave like an idealized firm with regards some kinds of knowledge and an idealized market with regards to other kinds of knowledge. More specifically, one may observe that a given organization allows its workers to coordinate via decentralized interactions when coordination depends on the use of highly tacit or highly dynamic knowledge, while using hierarchical 'command & control' when coordinating over knowledge that is low on the scale of tacitness and dynamism.

From an empirical point view one would also need a measure of the tacitness and dynamism of knowledge. This is a particularly important matter because a vast majority of the literature which derives a theory of the firm from the nature of knowledge assumes that tacitness is a binary attribute. Our approach in this paper has been very different. We developed a model which explicitly relies on tacitness being more a matter of degree than kind. The tacitness of the knowledge used within an entity would have to be elicited through microeconomic studies, perhaps even relying on questionaries administered to workers. Needless to say, it would be useful to corroborate the data elicited through questionaries with the ability of workers to transfer knowledge in performing tasks. The dynamism of knowledge too can be measured in a similar manner, though measures of the dynamism can rely more on objective criteria and less on worker responses to questionaries. This is because the determinants of the degree of dynamism of knowledge are less personal, having more to do with the technical aspects of production in an industry or the rapidity of changes in consumer preferences.

Much remains to be done in studying the institutional structure of production from a knowledge point of view. As to how firms and markets of various sizes and kinds emerge from individuals gathering, using, and communicating knowledge remains largely unknown. Coase (1988, p. 47) spoke of the institutional structure of production as "galaxies forming out of primordial matter". Perhaps Coase's ideal model would begin with individuals pursuing their goals in different kinds of knowledge environments, choosing to form relations that involve particular forms of collecting, processing, and communicating knowledge, ultimately generating structures that somewhat resemble the whole complex of arrangements we see outside the window. The model would need to incorporate factors like the cognitive limitations of the decision-making authorities within a firm (Simon 1965), the problems associated with passing instructions down a firm's hierarchy (Tullock 1997), and the role

of market microstructure in determining exchange costs (Madhavan 2000). Such a model is years ahead of our preliminary analysis. We have done little more than suggest that the institutional type and internal structure of institutions are shaped by a common factor, and that the factor is the nature of knowledge.

A Comparing the ideas developed in this paper with those in the literature on knowledge and information based theories of economic organization

Over the years, a wide variety of answers have been proposed to the question of why some activities are organized through markets and others through firms. Williamson (1971) and Alchian and Demsetz (1972), among others, argue that firms exist because markets fail in the presence of opportunistic behavior. This constituted significant progress over the earlier view that economic organization is determined by technology alone (Barnard 1938). Some scholars however found opportunistic behavior explanations to be unsatisfactory (Hart 1989). Coase (1988, p. 44) recalls that during his empirical work in the 1930s, he found himself more worried about opportunistic behavior than the businessmen who engaged in market contracts. This is not surprising. Markets have a variety of ways to solve problems associated with opportunistic behavior including reputation and social norms (Hill 1990; Ghoshal 2005). Furthermore, firms are not immune to moral harzard and adverse selection problems (Ghoshal and Moran 1996). As Coase (1988, p. 43) noted, opportunistic behavior does not necessarily make the market more costly than the firm and therefore may not explain the division of economic activities between the two institutions.

Knowledge-based theories and information-based theories of economic organization emerged in response to these critiques. The ideas proposed in this paper fall within this literature. One of the significant contributions of this paper is that we attempt to explain 'the organization of the economy' and 'the internal structure of the firm' using a unitary factor. Most knowledge and information based theories either explain the internal structure of the firm (Aoki 1986), or the division of economic activity between the firm and the market, but not both. Nickerson and Zenger (2004, p. 617) is one of the few papers which simultaneously studies the question of "boundary choice (i.e., internal versus external) *and* the choice among alternative internal approaches to organizing". They however do not attempt to solve the problem from the point of view of coordinating dispersed knowledge. In what follows we compare the ideas developed in this paper to some of the most relevant papers on knowledge and information based theories of economic organization.

A.1 Knowledge-based theories

Some of the literature on knowledge-based theories of the economic organization grew out of Penrose (1959) and Cyert and March's (1963) work on economic organization. While the literature on firms as knowledge-entities is large, only a subset of the literature compares the costs of using the firm to the cost of

using the market. In so far as we seek to understand the architecture of economic systems, comparing the costs of alternate arrangements of organizing economic activity is the crux of the matter. Among the theories which compare firms and markets, one set of theories compare firms and markets in *producing* knowledge (Langlois 1992; Kogut and Zander 1992; Langlois 2013), while another set compares the two mechanisms in *coordinating* knowledge (Grant 1996; Conner and Prahalad 1996). Naturally, the ideas developed in this paper belong to the second set of theories. This paper is unique among the second set in so far as it presents a formal model of the transmission of knowledge and its impact of economic organization.

Grant begins with Hayek's claim that the basic economic problem is how to coordinate the plans of economic actors in a system where knowledge is widely distributed. Grant accepts the view that markets are efficient at using knowledge, but claims that this is not true for all kinds of knowledge. He argues that markets cannot integrate knowledge that is non-rival and tacit, and firms exist because markets fail to coordinate activities that involve the use of such knowledge. Conner and Prahalad argue that firms are better than markets at using knowledge because they allow individuals to use knowledge that they do not fully possess or fully understand. Grant and Conner and Prahalad differ from Hayek and Polanyi's thesis that tacit knowledge is best used through distributed interactions rather than central control. In contrast to Grant and Conner and Prahalad, our setting closely aligns with Hayek and Polanyi's thesis on the use of tacit knowledge.

It is worth noting some of the defining features of our argument which mark its boundaries and therefore distinguish it from other knowledge-based theories. *First*, the literature on knowledge-based theories of the firm uses the word 'knowledge' in many senses, including the 'relations between individuals'. Following Hayek, we use the word knowledge to mean attributes possessed by individuals and not the relations between individuals. *Second*, knowledge has dimensions other than dynamism and tacitness. For instance, Tsoukas (1996) distinguishes between four kinds of knowledge: explicit knowledge held by individuals, explicit knowledge held by the firm, tacit knowledge held by individuals, and tacit knowledge held by the firm. We limit ourselves to two dimensions of knowledge held by individuals. *Third*, we do not study the ways in which tacit knowledge is codified and converted into more explicit knowledge, see Zack (1999), Haldin-Herrgard (2000), and Bhardwaj and Monin (2006) for such an analysis. We assume the nature of knowledge to be an exogenous variable that influences the nature of economic organization. The purpose of this assumption is to isolate and study the impact of knowledge on economic organization; it is not to deny the bi-directional relation between the nature of knowledge and economic organization. *Fourth*, we study the problems associated with centralizing knowledge from workers, we do not study the problems associated with passing instructions to workers. See Tullock (1997) and Simon (1965) for a discussion on costs and frictions associated with communication from managers to workers.

A.2 Information theoretic literature

The information theoretic literature studies firms and markets as alternate arrangements of processing information. Within this literature, our paper is closely related to Sah and Stiglitz (1988), Bolton and Farrell (1990), Radner (1992), and Stein (2002). Sah and Stiglitz (1988) study how centralized and decentralized systems aggregate errors in human decision making. Bolton and Farrell compare centralized and decentralized systems in solving coordination problems when information is private. They argue that decentralized systems produce lower-cost solutions but involve delay or duplication. Radner studies how the firm processes information to derive its optimal structure. Stein studies the dependence of internal structure of the firm on information. He argues that the performance of hierarchies improves with the ease of passing information, an insight largely consistent with our own.

While our study incorporates features of the afore noted studies, it differs from them in significant ways. Sah & Stiglitz model the market as a system in which one agent considers a project after it has been rejected by another agent. They do not allow for parallel decision-making in the market. Massively parallel interactions are however an essential feature the market (Axtell 2003). We model the market as a system in which agents make decisions in parallel without knowing what other agents do. Bolton & Farrell study the problem of entry in a decentralized system between two agents who do not know each other's costs. They however do not allow the agents to communicate with each other. We believe the problem of communicating private knowledge plays an essential role in determining the architecture of an economic system. We allow agents in the market and the firm to communicate with each other. Radner studies how firms solve non-associative problems, which are problems whose parts can be solved independently of each other. We study how the market and the firm solve a coordination problem which by its very nature is associative. Furthermore, neither Radner nor Stein compare the market and the firm as alternative mechanisms for using different kinds of information. In short, we address a gap in the literature by studying parallel interactions between agents who communicate with each other in both the market and the firm.

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Vipin P. Veetil Vipin P. Veetil has a PhD in economics from George Mason University. His areas of research interest include agent-based modeling and monetary economics. He currently works as an Assistant Professor at the Indian Institute of Technology Madras.