Technical Change and Organizational Transformation

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Abstract

Toward theoretically studying the impact of technical change on the organization of work and management, this paper proposes a novel account to the allocation and coordination of knowledge within the organization. An organization is modeled as a team of workers and a hierarchy of managers. While workers need to acquire complementary knowledge to execute those tasks required for the organization to be productive, managers have to arrange for the efficient allocation of pending tasks to those workers possessing the appropriate knowledge. As such, managers require a different kind of knowledge – I call it 'meta knowledge' – about the knowledge requisite to execute a specific task (but not the requisite knowledge itself) as well as about who in the organization possesses such requisite knowledge. Furthermore, they must communicate the respective task to the person with the appropriate knowledge. The key trade-offs therefore occur between the acquisition costs of the different knowledge types and the costs of communication. Such trade-offs determine the optimal task design, the optimal degree of specialization in the workforce, and the optimal structure of hierarchy. At the same time, they allow for a differentiated analysis of technical improvements and their organizational impact.

Keywords: Communication; Coordination; Hierarchy; Information and communication technology; Knowledge; Technical Change

JEL classification: D83; J21; L23; M54; O33

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I. Introduction

Technical change is certainly one of the most profound forces shaping organizations and their economic environment. Even if fundamental improvements that still underlie current organizational paradigms date so far back as the late 18th century (e.g. the beginning of automation), technical development remains among the most important drivers of organizational change to the present day. Accordingly, the research interest it has attracted has been large. Especially the development of modern information and communication technology (ICT) in the last decades has sparked a vast literature scrutinizing its impact on organizations, human resource practices, labor markets and mediated effects. Nonetheless, theoretical explanations remain riddled with significant explanatory gaps. One of the most manifest puzzles is that the development of ICT should according to theoretical predictions (e.g., March/Simon 1958, Becker/Murphy 1992, Milgrom/Roberts 1992) facilitate coordination and thus *foster specialization* and *greater centralization* of decision making (as decisions by upper management become better informed) but is in fact accompanied in many cases by 'new workplace practices' (such as teamwork, broader task assignment, multitask learning or job rotation) as well as flatter hierarchies that effectively reflect a *lower degree* of specialization and more *decentralized* decision making (e.g., Greenan/Guellec 1998, Brynjolfsson/Hitt 2000, Bresnahan/Brynjolfsson/Hitt 2002).

Further (and as it will turn out, connected) explanatory ambiguities concern the notions of 'technical change, 'ICT' and 'organization' themselves. Take for example the notion of 'ICT': Although indiscriminately used as a monolith in most of the pertinent literature, it actually stands for a quite amorphous bunch of different technologies, and it is far from clear how improvements in so disparate applications as electronic data transfer, management information systems, computer-aided manufacturing or expert systems impact organizational design. Similarly, one would expect that this impact would crucially depend on *where* such applications are deployed within an organization. Improvements in a computer system used by the management to coordinate activities of line workers could arguably have a quite different effect on organizational design than improvements in a computer system supporting the worker on the shop floor. Yet almost all accounts provided thus far have drawn a picture of an organization (as well as of technical development) far too nebulous to allow for fine-grained analysis. This lack of differentiation is usually accompanied by a lack of comprehensiveness. Technical change in general and even the more specific occurrence of advancements in modern ICT blend not only a wide and heterogonous variety of developments. They also exert influence on organizations via a nontrivial number of channels and mechanisms, jointly producing a no-less amorphous multitude of effects. Most studies, however, focus on just one or two of such effects (e.g., changes in communication or knowledge acquisition costs) and thereby fail to capture the inherent complexity of their object, with important consequence.

The aim of this paper therefore is to provide a more differentiated and comprehensive account of the relation of technical change to organizational transformation, integrating several mechanisms of impact and allowing for a multitude of effects produced. I achieve this by developing a fresh approach to the allocation and coordination of knowledge within the organization. In this approach, the organization has to solve a specific set of problems to be productive.[1] These problems differ in their quality, meaning variation in both the knowledge required for their solution and in the frequency of their occurrence. As knowledge is costly and taxes the scarce cognitive capacity of bounded rational workers, workers can economize on their knowledge acquisition costs by specializing in a subset of the total set of potential problems. This, however, gives rise to problems of coordination and matching, as pending problems must be allocated to workers possessing the specific knowledge adequate to their solution. Therefore it proves efficient that some members specialize in coordination itself. These so-named managers require knowledge different in kind from the 'object knowledge' required of and by workers; I call this knowledge 'meta knowledge'. Meta knowledge comprises both knowledge about what specific object knowledge is needed to solve a given problem (but not this requisite object knowledge itself) as well as knowledge about who in the organization possesses such needed knowledge (or who at least possesses the meta knowledge about who possesses it).[2] As managers are likewise limited by bounded rationality, and as meta knowledge is also costly, specializing in a subset of problems and of workers to be coordinated economizes on the extent and costs of meta knowledge acquisition. Such specialization, however, entails two consequential issues: First, managers have to coordinate their activity and interaction and thus themselves need to be organized. Second, interaction between managers incurs communication costs, as problems have to be referred between managers and finally to the adept worker. With respect to the first issue, I show that the optimal organization of management itself is just a hierarchy whose basic properties are in turn determined by the trade-off between costs of meta knowledge acquisition and communication (which addresses the

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[1] 'Problem (solving)' and 'task (execution)' are frequently used synonymously in the related literature and so too in this paper. They describe the basic activities in an economy.

[2] Although this terminology – indeed, the distinction itself – leans on the philosophical concept of 'object' and 'meta language' introduced by Tarski (1935, 1936), which has also gained relevance in the realm of computer science, the use of it here has nothing to do with the foundation of knowledge. Rather, I use it to emphasize the characteristic feature of knowledge (just like language) that it can relate to both real world objects and to knowledge (language respectively) itself.

second consequential issue). Hierarchies are therefore understood as problem allocation devices, and incorporating them into the model of knowledge and production yields an integrative account of the organization of work and management.

This account lays the groundwork not only for a more differentiated analysis of technical improvements sorted by the kind of technology and its field of application (e.g. fax or e-mail affecting communication costs vs. expert systems or computer-aided manufacturing on the shop-floor affecting object knowledge acquisition costs vs. enterprise resource planning or management information systems affecting meta knowledge acquisition costs). It also gives us a means by which to make some further effects related to technical change more amenable to analysis, where such effects include increasing labor productivity and an increasing specialization among firms. In the results spelled out below, I finally use this framework to account for the above-identified conundrum.

There have of course been other attempts to explain organizational design and the impact of technical change that have focused on information processing and on knowledge allocation within organizations. Particularly closely related to my approach is the information-processing literature (Radner 1992, 1993; Radner/Van Zandt 1992; Bolton/Dewatripont 1994; Van Zandt 1999a; Van Zandt/Radner 2001; see Van Zandt 1998 and 1999b for comprehensive surveys) and the type of economic models presented by Garicano (2000) and Garicano/Rossi-Hansberg (2004, 2006). As in this paper, both accounts leave incentive considerations aside and focus on bounded rationality (i.e. restrictions in information processing, knowledge acquisition and communication) to explain the existence and form of specific organizational structures such as hierarchies. Along these lines, they also provide frameworks to study the impact of advanced ICT on the organization of work and management. Compared to these literatures, however, my approach draws a far more fine-grained picture of the organization. The information-processing literature, on the one hand, essentially treats all tasks and agents within the organization as homogeneous. It therefore cannot account for the specialization of agents in terms of skills and capabilities, and it neglects the crucial problems of knowledge acquisition and task-agent matching.

Garicano-type models, on the other hand, do differentiate tasks and agents in terms of knowledge, but they do so only halfway, as the agents of a given hierarchical level remain homogenous. Furthermore, by equating managers with specialized problem solvers, they not only blur the important distinction between the operational and the administrative side of business, but they also land themselves with a number of implications scarcely consonant with empirical observations of ‘real-world’ organizations (e.g., the delegation of tasks up, instead of down, the hierarchy; or the CEO as either most specialized problem solver or omniscient pundit). The approach presented in the following, in contrast, makes a clear distinction among ordinary line workers, experts (as specialized problem solvers and as found, for example, in R&D- or IT departments but rarely in the upper echelons of organizations), and managers (as administrative coordinators). It also considers the different directions of referral up and down the hierarchy and allows for multifaceted forms of specialization, including within the same hierarchical rank. As a consequence, my model allows a more subtle assessment of the organizational impact of technical change.

The paper proceeds as follows. Section II considers related literature, placing the main emphasis on a critical discussion of comparable approaches to the allocation and coordination of knowledge within organizations, from which a large part of my motivation to develop a fresh approach stems. Section III presents the model of knowledge and production and introduces hierarchies as allocation devices. Furthermore, in the course of developing the model, I derive a number of results that pertain to general properties of optimal organizational design and that are informative in their own right. Section IV carries out some comparative-static analyses, scrutinizing the impact of exogenous parameter changes on the organization of work and management. The obtained results are afterwards related to different aspects of technical change, yielding an integrative account to its effects on the organization of work and of management. Section V concludes with a discussion of some limitations and avenues for further research. All proofs are relegated to the appendix.

II. Related Literature

The literature on technical change and its impact on the organization of work and management is rather vast, and its comprehensive review would certainly exceed the scope of this paper. Numerous empirical studies have documented ‘new workplace practices’ (such as teamwork, broader task assignment, multitask learning or job rotation) and related organizational transformation processes towards a lower degree of specialization and flatter hierarchies for a number of countries such as the U.S. (e.g., Lawler/Mohrman/Ledford 1992, Osterman 1994, Rajan/Wulf 2006), Japan (e.g., Aoki 1990), as well as several European and other developed countries (e.g., NUTEK 1996, 2000, OECD 1996, 1999, European Foundation 1997, 1998, Gallie et al. 1998, Caroli/Van Reenen 2001). Further work shows that these organizational changes are indeed strongly correlated with technical change at the firm level, especially with the adoption of modern ICT (e.g., Greenan/Guellec 1998, Brynjolfsson/Hitt

2000, Bresnahan/Brynjolfsson/Hitt 2002). In rather stark contrast, however, theoretically oriented work providing a conceptual account of this relation is quite sparse. Most of this work is concerned rather with the labor market implications of technical change (particularly changes in skill demand and wage inequality) and secondarily considers organizational change merely as a mediating factor (cf. the surveys Aghion/Caroli/García-Penalosa 1999 and Acemoglu 2002). Among the few studies placing their main emphasis on the organizational impact of technical change are Milgrom/Roberts (1990, 1995), Lindbeck/Snower (2000) and Dessein/Santos (2006). All these papers, however, restrict their attention to the organization of work – neglecting management – and focus on examining complementarities between technical advancements and organizational measure on the shop floor. They therefore significantly differ in both scope and approach from my attempt here.

More closely related for their focus on hierarchical structures, as well as on communication, information processing and knowledge acquisition within organizations, are the two literatures already mentioned. The information-processing literature views organizations as processors of exogenously given information, which is simultaneously received, aggregated and passed on by different subunits or members who are themselves interpreted as decentralized information processors. On this basis, arrangements of these (sub-)processors and their optimal communicational linkages are analyzed under considerations of information processing performance, such as the reduction of delay or the economization on necessary resources (e.g. communication costs and the number of processors used). This approach therefore constitutes a framework for analyzing developments in the ICT. Although this approach has delivered important insights on the influence of organizational design on performance in information processing, the parallelism of organizations with parallel-processing computers has narrowed the scope of analyses and the insights derived. The form of information processing utilized in analysis – mainly associative operations such as number addition or the finding of extrema – is obviously adopted from computer science, and it disregards the great variety of (information processing) tasks relevant to organizations. Coupled to the homogeneity of tasks considered is an assumed conformity of characteristics pertaining to each processor, which cannot account for the specialization of agents in terms of skills and capabilities, and which neglects the crucial problems of knowledge acquisition and of matching tasks with those agents adequately knowledgeable for their execution.[3]

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[3] An exception is Bolton/Dewatripont (1994), who attempt to allow for specialization. This attempt, however, is not only narrowed down to the sole aspect of processing and communicating information, but it remains somewhat ad-hoc, as it does not explicitly incorporate task heterogeneity.

In this respect, my approach is certainly more closely related to that presented by Garicano (2000) and subsequently extended by Garicano/Rossi-Hansberg (2004, 2006) and Antràs et al. (2006). Garicano develops a notion of 'knowledge-based hierarchies' as a mechanism for allocating problems to appropriately trained workers. Whereas workers at the lowest level ('production floor') are capable of solving only the easiest (and most common) problems, more difficult (and more exceptional) problems are passed on to a next level, which consists of more specialized problem-solvers. If neither they are up to the problem, they refer it to the next level of even more specialized problem solvers and so on, until the problem is solved or until the highest level of the organization is reached. Thus, by matching problems and appropriately trained workers, hierarchies economize on costly knowledge acquisition at the cost of the communication required. Without doubt, this approach has many appealing features and has proven very fruitful in application to several topics of current economic research, not least in analyzing the impact of improvements in ICT. On closer inspection, however, it can be found to be built on a conflation of experts and management within organizations. While experts – one may think of scientists in the R&D-department, of creative individuals in the marketing department, of computer specialists, and even of the facility manager able to mend the out-dated heating system – are in fact highly specialized problem solvers, they are hardly found at the upper echelons of organizations. Nor is their efficient organizational pattern necessarily hierarchical (in fact, particularly with 'knowledge workers', nonhierarchical forms like teamwork have often proven to be superior, as in e.g. Caroli/Greenan/Guellec 2001 and Bresnahan/Brynjolfsson/Hitt 2002). Managers, on the other hand, are rarely seen to tackle specialized problems on their own (e.g. to personally shake test tubes, conceive of a fancy marketing campaign or to tinker with the heating system with their own hands), but rather to delegate such problems to experts, coordinating the experts' respective activities. Accordingly, they need a completely different range of skills and knowledge than those attributed to specialized experts. In this spirit, for instance, it seems quite misleading to regard the CEO as the organization's most specialized problem solver (or, in the model variant of cumulative knowledge acquisition (cf, Garicano 2000, pp. 894 ff.), as omniscient pundit), since she probably resembles more the generalissimo than the narrowly-focused specialist; it is more conceivable that *she* will consult a range of experts down the hierarchy on special issues than the other way around.

This discrepancy ties into several further shortcomings of Garicano-type models. For example, the unidirectional referral of problems up the hierarchy hardly relates to real-world organizations, where tasks are evidently far more frequently delegated down the hierarchy. Furthermore, the differentiation of qualifications and the distribution of knowledge among staff remain somewhat inchoate, as Garicano-type models allow for heterogeneity only between different hierarchical levels and neglect ‘horizontal’ specialization (which means, for instance, that they offer no means to actually differentiate the creative type in the marketing department from the facility manager belonging to the same hierarchical rank). The approach presented here, in contrast, not only makes a clear distinction between experts as specialized problem solvers and managers as administrative coordinators, including their respective area of activity and their differing competences and requisite qualifications. It also considers the different modes and directions of referral up and down the hierarchy, and it allows for multifaceted forms of specialization, including horizontal (i.e., for example functional, regional or product-focused) specialization within the same level of hierarchy.

III. A Model of Knowledge and Production

A. Production and the Acquisition of Object Knowledge

In the following, I characterize the basic activities of an economy as solving problems. Every organization must solve a specific set of problems to be productive. The problems range for a car manufacturer, for instance, from drawing up a blueprint of a model to designing and producing or procuring each of its single components, from the creation and coordination of fancy ad campaigns to the recruitment and training of smart salesmen, from the management of the staff canteen to the assignments of the company’s parking lots – to name just a few. These problems differ obviously in their quality, meaning variation in both the knowledge required for their solution and the frequency of their occurrence. Let us denote the set of all possible problems by $Z \subset R^{+}$ and assume that the corresponding distribution F(Z) and density f(Z) exist and are continuous and non-atomic. For convenience, and without loss of generality, suppose the problems to be ordered by their frequency, so that f(Z) is non-increasing. Furthermore, I assume that all problems within a specific set $[0, Z_H]$ must be solved.

Problem solving requires an apt amount of knowledge. To differentiate this knowledge from a different type introduced later, I name it ‘object knowledge’. Accordingly, the amount of object knowledge held by an individual may be approximated by the set of problems she is able to solve. I employ the Lebesgue measure and express this amount by the size of the interval of problems covered by a worker’s knowledge. Reflecting the bounded rationality of workers, I assume the acquisition costs of object knowledge to be a convex function of this amount, i.e.,

$C_{OK}(Z)$, such that $C'_{OK} > 0$ and $C''_{OK} > 0$ and thus suppose that workers may differ in the knowledge they acquire but are homogenous in their talent or learning aptitude (i.e., in their cost function of object knowledge acquisition). Furthermore, workers are restricted in their working capacity. The maximum workload of each worker is limited to $F(Z_H)/n$, such that solving all problems requires n workers.[4] The knowledge-acquisition costs-minimizing allocation of problems and knowledge to workers is then reflected in Figure 1.

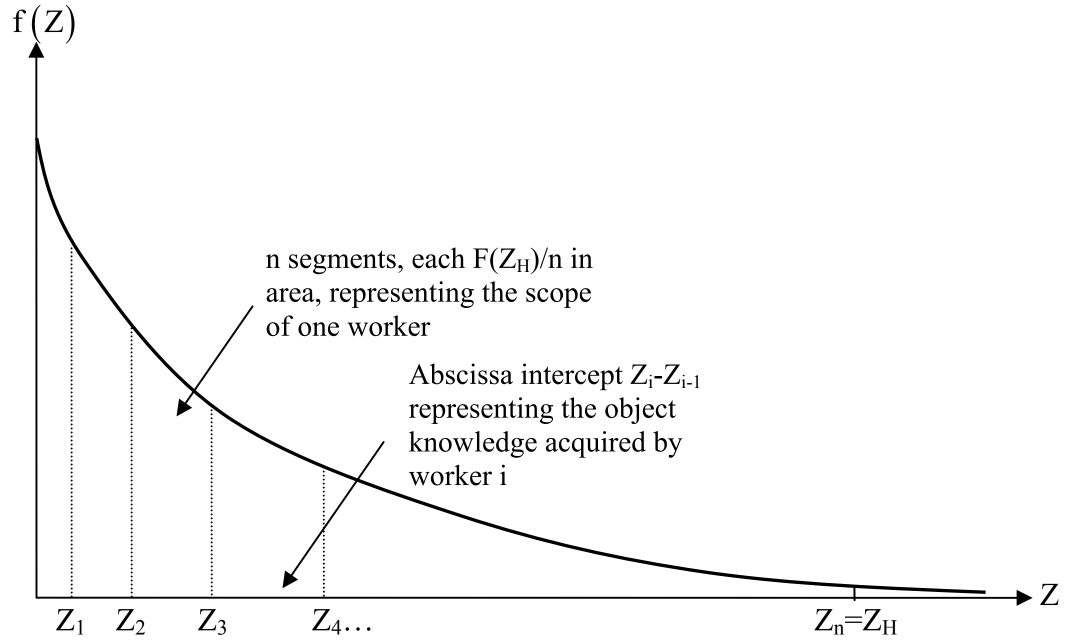

Figure 1 Knowledge-cost-minimizing allocation of knowledge to workers and workers to problems

The aggregate amount of problems $F(Z_H)$, i.e. the area beneath the density function up to Z_H, is evenly partitioned. Each segment represents the scope of one worker and the pertaining abscissa intercept the object knowledge held by her. That knowledge acquisition costs are minimized is assured by avoiding an overlap between the knowledge sets of workers, implying perfect specialization. Minimal knowledge acquisition costs are accordingly given by

$$C^{OK} = \sum_{i=1}^{n} C_{OK}\left(Z_i - Z_{i-1}\right) = \sum_{i=1}^{n} C_{OK}\left(F^{-1}\left(\frac{i \cdot F(Z_H)}{n}\right) - F^{-1}\left(\frac{(i-1) \cdot F(Z_H)}{n}\right)\right). \quad (1)$$

Note, that workers in this model can be differentiated with respect to two aspects. On the one hand, one can differentiate them by the *kind* of problems they are able to solve, i.e., by the *kind of object knowledge* they acquire, which reflects their functional (or product-oriented or regional) specialization. On the other hand one can differentiate workers by the *range* of prob-

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[4] In the following I assume full utilization of a worker's capacity. Alternatively I could impose a fixed cost per worker high enough.

lems they are able to solve, i.e. by the *amount of object knowledge* they hold, which immediately corresponds to the frequency and uniformity of problems they encounter. This latter differentiation thus allows us to roughly split the workforce into ordinary (or line) workers, who focus on a small range of object knowledge concerning the most common problems (represented rather on the left side of Figure 1) and experts (or staff workers), who hold a comparatively greater amount of object knowledge pertaining to more exceptional problems (represented rather on the right side of Figure 1). In this vein, the model allows for two different types of 'horizontal' specialization which constitutes a difference (and extension) to the model types discussed previously.

B. Hierarchy as a Matching Device

This kind of specialization by workers, however, gives rise to issues of coordination and matching, as pending problems must be allocated to workers possessing the specific knowledge adequate to their solution. In the following, I consider this allocation of problems to workers as an essential part of the production process. Several procedures are in essence conceivable. A very primitive matching mechanism would consist of random communication. Under such a scheme, a worker who encounters a problem for which solution she lacks the appropriate knowledge arbitrarily turns to her colleagues until she finds one knowledgeable. A more sophisticated (and under a wide range of circumstances, more efficient) approach iterates the concept of specialization at a higher level by providing for some organization members specialized in allocating problems - let us call them managers -, while others - ordinary workers - focus on their solution. Two different modes of such manager-mediated problem matching are roughly conceivable, distinguished by the direction of the allocation process. With *top-down* problem allocation there is one manager 'at the helm' navigating problems, who then subsequently refers emergent problems to appropriately skilled workers, perhaps by way of further managers. *Bottom-up* problem allocation, on the other hand, resembles more the setting of random communication. Here workers first encounter problems in the course of their work. Unless they have the object knowledge to tackle the specific problem, they refer it to a manager, who is then in charge of finding the properly skilled worker. Both modes claim some evidence in empirics. While the top-down mode takes management as a process of conscious task design and authoritarian task assignment, bottom-up allocation rather reflects the notion of 'management by exception', as considered by Garicano-type models (for an interpretation in this vein see Garicano 2000, p. 897 f.) and is given anecdotal evidence, for example, by Sloan (1924).

Except for a few caveats, however, this differentiation does not make a great difference with respect to the results, and I will therefore restrict my attention to the case of top-down problem allocation by managers.[5] For this purpose, I will now introduce a new kind of knowledge informing the process of targeted problem allocation, which in contrast to the object knowledge considered thus far I call 'meta knowledge'. Leaning on the philosophical concept of 'object' and 'meta language' introduced by Tarski (1935, 1936), this distinction utilizes the characteristic feature of knowledge (just like language) such that it can relate to both real world objects and to knowledge (language) itself. Therefore, meta knowledge is basically knowledge *about* (object or meta) knowledge, but it is not this knowledge itself. In the wider sense it also comprises, for example, knowledge about the place where this knowledge is stored or for what it is useful. Examples might include keywords of a scientific paper, records in a library catalog or tags indexing internet pages (including the knowledge where to find these resources and whom or what purpose they may serve). In our context, meta knowledge comprises both knowledge about what knowledge is requisite for the solution of a specific problem (but not the requisite knowledge itself) as well as knowledge about who in the organization possesses it (or at least who possesses the meta knowledge about who possesses it). The extent and manner of this knowledge are accordingly determined by the set of problems as well as by the set of people to be mapped. This suggests a conception of the amount of meta knowledge held by a manager as a function of both the range of problems she is able to assess (as in the previous section denoted by Z) and the number of people to whom she is able to delegate problems (s). By analogy to object knowledge, I assume that meta knowledge comes at costs $C_{MK}(Z,s)$, where $C_{MK}(Z,s)$ is a convex increasing function of Z as well as of s , which means (with neglect of integer constraints)

$$\frac{\partial C_{MK}}{\partial Z} > 0\,,\ \frac{\partial^2 C_{MK}}{\partial Z^2} > 0\,,\ \frac{\partial C_{MK}}{\partial s} > 0\,,\ \frac{\partial^2 C_{MK}}{\partial s^2} > 0 \text{ as well as } \frac{\partial^2 C_{MK}}{\partial Z \partial s} > 0\,. \qquad (2)$$

Just as with workers, managers may differ in the amount and quality of knowledge they acquire, but they are homogenous in their talent or learning aptitude, which is to say in their meta knowledge cost function. Like workers, they are also limited by bounded rationality, as reflected by the convexity of this function.

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[5] Although I refer as a matter of convenience to the second mode merely as bottom-up allocation, bottom-up-top-down allocation were in fact a more exact description, as it indicates the similarities between a part of this process and top-down problem allocation. For a short discussion of the caveats see an earlier version of this working paper circulating as "Knowing How to Know: The Allocation and Coordination of Knowledge in Organizations".

In addition to knowing to whom to refer a specific problem, managers must communicate this problem to the person with the appropriate (object or meta) knowledge, i.e. to the aptly knowledgeable worker or to another manager. I assume a fixed cost C_C per act of communication.[6] A trade-off therefore occurs between costs of meta knowledge acquisition and communication. To see this, consider an organization consisting of n production workers. If there were only one manager responsible for problem matching, each problem delegated by this manager would entail only one act of communication; but the manager herself would suffer costs of meta knowledge acquisition of $C_{MK}(Z_H, n)$. In the opposite case, with one manager covering one worker, the costs of meta knowledge acquisition would accumulate to $n \cdot C_{MK}(Z_H / n, 1)$, which by (2) is lower than $C_{MK}(Z_H, n)$, but communication among managers would arguably resemble the case of random communication, requiring a far greater communication effort to match problems with workers. The optimal organization of management would therefore determine the number of managers as well as their linkages in terms of meta knowledge and communication so as to minimize the sum of communication and meta knowledge acquisition costs. Although the concrete design clearly depends on the specific parameterization, a few general results can be derived.

> PROPOSITION 1. Consider the case of top-down problem allocation where a set of problems initially assigned to one manager must be communicated to a number of specialized workers with mutually exclusive but communally exhaustive knowledge to solve these problems, possibly by way of further managers.
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> a) Then the matching costs (i.e. the sum of meta knowledge and communication costs) minimizing arrangement of these managers constitutes a hierarchy, i.e. a ranked tree.
> b) Except for integer constraints, this hierarchy is balanced, i.e. managers at a certain level of hierarchy each exhibit the same span of control.
> c) This span of control (weakly) increases from top to bottom.

The intuition for the first part a) is that a manager's meta knowledge assigns her a set of colleagues - either workers or other managers - to whom she is able to delegate tasks. It therefore constitutes a relation roughly equivalent to the 'superior-to' relation employed in building a hierarchy (which can be shown to meet further criteria to actually yield a ranked tree). Such a hierarchy is characterized by a basic trade-off already mentioned by Simon (1976, pp.

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[6] Such communication costs may reflect several aspects of resource usage in communication processes. First but of mostly minor importance are mere transmissions costs, i.e. costs of using a channel. The sender's costs of encoding as well as the receiver's cost of decoding and absorbing the information are often much more pronounced (cf. the discussion in section IV.B). But even costs of attendant delay may be included.

26 ff.) between the principle of limiting the span of control so as to economize on managerial resources (here a manager's meta knowledge) and the principle of limiting the distance between the head and the production level so as to economize on communication costs. The basic message of the proposition's second part b) holds that it is a balanced hierarchy that best mitigates this conflict.

This result is especially remarkable in that it derives the span of control entirely endogenously. Early studies of the characteristics of hierarchies usually regarded the span of control as an exogenous parameter (e.g., Beckmann 1960, Williamson 1967). A subsequent generation of contributors did endogenously derive optimal spans of hierarchies, but they still presumed some important properties, especially a unique span of control for each hierarchical level and, thus, the hierarchy to be balanced (e.g., Keren/Levhari 1979, 1983, Qian 1994). Still another approach undertaken in the information-processing literature (e.g., Radner 1993) succeeded in deriving all relevant properties endogenously, but had to accept some results that defied common real organizational patterns (e.g. pronounced skip level reporting, even directly from an ordinary worker to the CEO; profoundly irregular hierarchies). This model, in contrast, not only derives prima-facie acceptable predictions about efficient hierarchical structures under fairly general conditions, but by deriving the hierarchical structure from basic properties of the concept of meta knowledge, it also gives a very intuitive account for why hierarchies are an efficient coordination device and are so prevalent in organizations to begin with.

The third part of the proposition, by contrast, is consistent with several other theoretical results (e.g. Keren/Levhari 1979, 1983). Evidently, it reflects a form of specialization within management. Descending the hierarchy, problems become increasingly uniform, which means focused, for example, on a specific function, product or region. This reduces the share of cognitive capacity employed in assessing exceptional problems, which can in turn be devoted to the coordination of the activities of a greater number of subordinates. In consequence, the span of control tends to increase down the hierarchy, which also receives support from several empirical examinations (as, e.g., surveyed by Beckmann 1960 and Starbuck 1971).

Beyond meta knowledge acquisition and communication costs, the number of workers to be coordinated obviously has a decisive impact on the optimal hierarchy and accordingly the ressources required for top-down problem allocation. More specifically:

PROPOSITION 2. a) For a given number of workers n there is one optimal hierarchy minimizing matching costs.[7] This hierarchy is specified by the number of managers (M), its height (L), and the optimal span of control (s_i) for each hierarchical level $i \in \{1,\ldots,L\}$, whereby M, L, and the average span of control defined as $\overline{s} = \frac{1}{L}\sum_{i=1}^{L} s_i$ (weakly) increase in n.

b) The minimal matching costs C^M imposed by this optimal hierarchy increase with the number of workers to be coordinated n, *but on a decreasing scale*. More precisely, $C^M(n)$ is approximately a (weakly) concave function.[8]

The interesting point in this result is that it implies economies of scale in coordination. It was a common and long-standing belief that while production processes exhibit some kind of economies of scale, the opposite is true for the coordination and administration of organizations. Via accruing limitations to entrepreneurial capacity, increasing slackness, increasing delay in decisions, etc., administrative costs were thought to increase disproportionately in the size of the company (e.g. Robinson 1934). This constitutes diseconomies of administration, which at some point counterbalance economies of production and thus determine the optimal size of the firm. Beckman however challenged already in 1960 the common wisdom and successfully showed that, under fairly general conditions, the marginal costs of administration per worker are asymptotically constant but in no case increase without bound. Further contributions scrutinizing this issue via more sophisticated means have shown that diseconomies of administration depend rather precariously on the specific assumptions underlying the respective model and cannot be taken for granted (e.g. Radner/Van Zandt 1992, Van Zandt/Radner 2001). The result I derive goes yet further in that it unambiguously argues for economies of scale in administration. Do such economies of scale in coordination mean, however – particularly with further consideration for economies of scale in production –, that organizations should increase without bound? This of course would be a premature conclusion, as this model abstracts from some factors that potentially limit organizational growth (e.g., considerations for incentive problems and costs of delay).[9]

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[7] In some borderline cases there may be two hierarchies exhibiting the same matching costs.

[8] By 'approximately a (weakly) concave' I denote a function that is (weakly) concave except for a finite number of compact intervals.

[9] Incentive and control considerations seem to be especially promising candidates to establish substantial diseconomies of scale (e.g. Williamson 1967, Rosen 1982, Qian 1994), and their incorporation into the model discussed here would be a step towards a yet more realistic notion of real-world organizations.

C. An Integrative Account to the Organization of Work and Management

Integrating both parts of the model as developed in the previous two sections results in a team of workers responsible for solving the problems required for organizational productivity and in a hierarchy of managers in charge of matching these problems with aptly skilled members of the workforce. At the same time, it constitutes a multi-facetted trade-off between the costs object knowledge acquisition, meta knowledge acquisition and communication, which shapes the organization of work and management. Whereas so far the trade-off between meta knowledge acquisition and communication costs determined the optimal organizational design, an organization commands yet a further lever under this approach in terms of the degree of specialization in the workforce. This is to say, an organization can economize on matching costs by allowing overlapping knowledge sets of workers - a kind of knowledge slack - at the expense of object knowledge acquisition costs. In the extreme, each worker would acquire the complete amount of requisite object knowledge Z_H, which would render matching irrelevant at the outset (as each worker would be up to every problem) but which would result in massive object knowledge acquisition costs of $n \cdot C_{OK}(Z_H)$. Between the two opposite poles - workers having either completely distinct or identical knowledge sets - the workforce can be clustered in an arbitrary number $m \in [1, n] \cap \mathbb{N}$ of classes of equal size (let us call them 'shops'), where workers within each shop dispose of the same knowledge and where shops are mutually exclusive but communally exhaustive with respect to the requisite amount of knowledge Z_H. Shops in this sense represent an abstract concept, measuring the degree of specialization within the workforce and therefore the efficiency in using object knowledge for production. They need not (and hardly ever will) correspond to actual organizational entities.[10]

Treating communication and knowledge acquisition costs as well as the size of the organization as exogenous, the overall production costs C^P then constitute a function of the degree of specialization m. They are the sum of object knowledge acquisition costs $C^{OK}(m)$ and matching costs $C^M(m)$, the latter combining in turn meta knowledge acquisition costs $C^{MK}(m)$ and communication costs $C^C(m)$. More precisely,

$$C^P(m) = C^{OK}(m) + C^{MK}(m) + C^C(m) \tag{3}$$

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[10] Accordingly, the uniformity of shop size does not impair the generality of the results obtained but facilitates a rigorous analysis as it (in conjunction with the capacity constraint) assures that the shops are equal in their ex-ante probability of being competent with respect to a problem and are thus treated equally with respect to matching procedures.

where $C^{OK}(m)$ is given by analogy to (1) as

$$C^{OK}(m)=\sum_{i=1}^{m} C_{OK}\left(F^{-1}\left(\frac{i\cdot F(Z_H)}{m}\right)-F^{-1}\left(\frac{(i-1)\cdot F(Z_H)}{m}\right)\right)\cdot\frac{n}{m}. \tag{4}$$

$C^{MK}(m)$ sums up meta knowledge acquisition costs for each manager at each hierarchical level $i\in\{1,\ldots,L(m)\}$, where 1 denotes the top and L(m) the bottom level. L(m) is implicitly determined by

$$\prod_{i=1}^{L} s_i = m \tag{5}$$

where s_i refers to the span of control of level i. The product $s_1\cdot s_2\cdot\ldots\cdot s_{i-1}$ accordingly yields the number of managers in level i. Meta knowledge acquisition costs then amount to

$$C^{MK}(m)=C_{MK}(Z_H,s_1)+\sum_{i=2}^{L(m)}\left(\prod_{j=1}^{i-1}(s_j)\cdot C_{MK}\left(\frac{Z_H}{\prod_{j=1}^{i-1}s_j},s_i\right)\right). \tag{6}$$

$C^C(m)$, finally, is determined by the height of the hierarchy (i.e. the number of levels) and is given by

$$C^C(m)=L(m)\cdot C_C.^{11} \tag{7}$$

The optimal organization of work and management is then designed to minimize (3). This idea is captured by the next result.

> PROPOSITION 3. The optimal degree of specialization within the workforce is determined by optimizing the trade-off between acquisition costs of object knowledge and matching costs. More precisely, there exists a number of shops m^* reflecting the optimal degree of specialization which minimizes the overall costs of production as given by (3). This m^* at the same time determines the optimal the number of managers (M), the height of the hierarchy (L), and the optimal span of control s_i for each hierarchical level $i\in\{1,\ldots,L\}$.

This result essentially reflects an issue that has stimulated discussion in economics since at least Adam Smith's seminal work – the fundamental trade-off between specialization and

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[11] For convenience, this notation of communication costs neglects integer constraints and presumes that level L is filled by managers and that there remain no shops at this level. If that is not the case owing to integer constraints, (7) marks only an upper bound of communication costs. Furthermore, I normalize without loss of generality the amount of problems to unity, i.e. set $F(Z_H)=1$.

coordination.[12] Here, the benefits of specialization as well as the costs of coordination indeed take a specific form. On the one hand, it is the bounded rationality of workers that generates potential for economization on learning costs by confining the field of activity to which a worker attends. On the other hand, this gives rise to matching problems, as problems must be allocated to workers possessing the adequate knowledge. This brings us back to the puzzle motivating this effort. What impact will improvements in ICT have on this fundamental trade-off between specialization and coordination and therefore on the optimal organization of work and management? The next section aims to come to grips with this central question.

IV. The Impact of Technical Change on the Organization of Work and Management

A. Comparative-Static Analysis

Technical change in general and even the more specific advancements in modern ICT each bring together a wide and rather heterogeneous variety of phenomena and developments to produce a no less amorphous variety of influences and effects. To structure an approach to this multi-facetted and complicated set of relationships, and to make tractable a formal account of them, I examine several exogenous parameters of the model (i.e. communication and knowledge acquisition costs, worker's productivity, task variety) in turn, analyzing in this section their impact on the optimal organization of work and management. The next section then relates these parameters to a number of effects driven by or associated with technical change. Combining the insights from both parts, the subsequent section provides an integrative assessment of the impact of technical change on organizational structure and illustrates the main results by calculating some examples.

Acquisition Costs of Object Knowledge. Let us start the comparative-static analysis by focusing on object knowledge and the impact of a change in its acquisition costs on the optimal organization of work and management.

> PROPOSITION 4. As the per unit cost of object knowledge decreases, the optimal degree of specialization within the workforce (m), as well as the number of managers (M), the management-to-staff ratio (M/n) and the height of the hierarchy (L) (weakly) decrease.[13]

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[12] Recent contributors include among others Becker/Murphy (1992), Bolton/Dewatripont (1994), Hart/Moore (2005), Dessein/Santos (2006), Hecker (2008).

[13] This and all following propositions certainly work in both directions, i.e. in this case an *in*crease in the cost of object knowledge implies the opposite effect on the organization of workers and management. I state the direction most relevant for the further discussion. To obtain the opposite direction simply 'exchange signs'.

The intuition behind this result is quite clear. Specialization serves to economize on object knowledge acquisition costs by distributing the object knowledge requisite for production among workers. But it comes at the cost of coordination and matching. As attainable gains through specialization diminish due to decreasing per unit costs of object knowledge, they no longer outweigh high coordination and matching costs pushing for a lower degree of specialization. This in turn decreases the demand for coordination and thus the extent and complexity of the managerial apparatus.

Acquisition Costs of Meta Knowledge. Whereas a change in the cost of object knowledge directly impacts the organization of work, which then consequentially influences the organization of management, it is the other way round with meta knowledge.

> PROPOSITION 5. As the per unit cost of meta knowledge acquisition decreases, the optimal degree of specialization within the workforce (m) (weakly) increases, but the impact on the number of managers (M), the management-to-staff ratio (M/n), and the height of the hierarchy (L) is ambiguous.

In fact, there are two distinguishable effects whose interaction shapes this result. One effect results from shifting weights in the trade-off between meta knowledge acquisition and communication costs. A decrease in meta knowledge acquisition costs fosters increasing spans of control, which in turn leads to flatter hierarchies with a reduced number of layers (L) and managers (M), therefore saving on communication costs. As a consequence, matching costs – as the sum of meta knowledge and communication costs – decrease as well, which affects the additional trade-off between object knowledge acquisition and matching costs and which produces the second effect. As specialization now becomes cheaper, it will increase, counteracting in turn the effects on M, M/n, and L. The bottom line: The model yields clear predictions regarding the impact on the optimal degree of specialization, but the effect on the other parameter hinges on the specific parameterization.

Communication Cost. Changes in communication costs show the same twofold thrust of impact as seen for meta knowledge acquisition costs. Whereas the influence on the trade-off between object knowledge acquisition and matching costs is quite the same, the direction of impact on the second trade-off between communication and meta knowledge acquisition costs is naturally the opposite. The residual effect is described by the following result.

> PROPOSITION 6. As the costs per act of communication (C_C) decrease, the optimal degree of specialization within the workforce (m) as well as the number of managers (M), the management-to-staff ratio (M/n) and the height of the hierarchy (L) (weakly) increase.

Worker Productivity. Besides knowledge acquisition and communication costs, there are arguably further parameters mediating the impact of technical change on the organization of work and management. One of these is the productivity of work.

> PROPOSITION 7. As the productivity (or equally, working capacity) of workers increases, the size of the workforce (n), the optimal degree of specialization within the workforce (m), the number of managers (M), and the height of the hierarchy (L) (weakly) decrease, whereas the impact on the management-to-staff ratio (M/n) remains ambiguous.

An increase of worker's productivity obviously reduces the number of workers required, as the overall amount of work remains constant. At the same time the total amount of object knowledge required for production is spread over fewer workers, requiring each worker to increase her individually-held amount of object knowledge. This cost-increasing effect is the more pronounced the higher the degree of specialization in the workforce (and in the extreme case of zero specialization, i.e. m=1, completely extinguished). As specialization thus becomes less efficient, it will decrease, which in turn decreases the demand for coordination and thus the extent and complexity of the managerial apparatus. As both n and M therefore decrease, the consolidated effect on the management-to-staff ratio remains uncertain.

Task Variety. The last parameter I will discuss pertains to the variety of problems the organization as a whole must solve to be productive.

> PROPOSITION 8. As the task variety (Z_H) increases, the size of workforce (n), the optimal degree of specialization within the workforce (m), the number of managers (M) and the height of the hierarchy (L) (weakly) increase, whereas the impact on the management-to-staff ratio (M/n) remains ambiguous.

An increase in the task variety – while the underlying problem distribution remains unaffected – means on the one hand an increase in the total amount of problems to be solved and, therefore, in the size of the workforce. On the other hand it implies an increase in the total amount of object knowledge held by the workforce as a whole. This increases the potential of specialization, (over)compensating additional costs of coordination and matching, and results in a higher degree of specialization in the workforce and, accordingly, in an extended managerial apparatus. (The ratio of the effect on n and M remains uncertain).

Table 1 summarizes the results of this comparative-static analysis by relating changes in the exogenous parameters to their organizational impact.

	Size of workforce (n)	Degree of specialization (m)	Height of hierarchy (L)	Number of managers (M)	Management-to-staff-ration (M/n)
Object knowledge costs (C_{OK})	→	↗	↗	↗	↗
Meta knowledge costs (C_{MK})	→	↘	↕	↕	↕
Communication costs (C_C)	→	↘	↘	↘	↘
Productivity of work ($F(Z_H)/n$)	↘	↘	↘	↘	↕
Task variety (Z_H)	↗	↗	↗	↗	↕

Table 1 Organizational impact of an increase in exogenous parameters (↗= weak increase, ↘= weak decrease, ↕= ambiguous impact, →= no impact)

B. The Impact of Technical Change on Exogenous Parameters

The previous section derived the impact of changes in the exogenous model parameters on the optimal organization of work and management. But how are these parameters actually influenced by technical change? In the following, this question is tackled by relating a number of effects driven by or associated with technical change to the parameters discussed above.

Acquisition Costs of Object Knowledge. That technical progress indeed reduces the acquisition costs of object knowledge is driven by at least two effects. On the one hand, modern production technology substitutes more and more for the object knowledge held by workers. On the other hand, improvements in education systems and vocational training programs associated with technical change have led to a significant increase in the supply of object knowledge embodied in educated workers. With respect to the first trend, automated tools, programmable manufacturing equipment, expert systems and computer-aided production and design (e.g., CAD, CAM, CIM) incorporate object knowledge to an increasing degree. This economizes on the cognitive capacity of workers, allowing them to qualifiedly handle a quite larger range of task without incurring a significantly greater cost in the amount of training they require (even if the contents of such training change significantly). To take up an example from Milgrom/Roberts (1990), modern CAD systems immediately translate a product design into coded instructions, which can then be used by programmable manufacturing equipment without workers having to assimilate and implement them into new production patterns and processes. Technical change therefore substitutes for the object knowledge held by individual workers and consequentially lowers object knowledge acquisition costs per task both on an absolute scale and at the margin.[14] This result is reinforced by the significant increase in education and skill-building among workers over at least the last fifty years (e.g., Autor/Katz/Krueger 1998, Acemoglu 2002). Although the debate is not yet settled as to whether this trend is actually technology-driven or technology-driving, the increasing supply nonetheless has a further depressing effect on costs of object knowledge.[15]

Acquisition Costs of Meta Knowledge. Compared to object knowledge, the effect of technical change on meta knowledge acquisition costs is more ambiguous. At first sight, advancements in the modern information technology (IT) obviously facilitate the coordination of specialized workers and therefore economize on managers' cognitive capacity. Especially modern management information systems, workflow systems, enterprise resource and production planning systems as well as forecasting and controlling tools significantly support managers in inventory and capacity control, as well as in resource allocation, work planning, task assignment and the supervision of worker activities. Furthermore, decision rules and instructions embodied in automated tools (e.g., McDonald's fixed-programmed cash register or computer-based credit approval processes) guide workers through work processes without taxing a manager's scarce cognitive resources. On closer inspection, however, the substitutability of IT for meta knowledge remains limited and confined to quite simple, standardized tasks and decisions. With more complex and idiosyncratic tasks, evidence points rather to a complementary than a substitutive relationship (e.g., Autor/Katz/Krueger 1998, Bresnahan 1999, Bresnahan/Brynjolfsson/Hitt 2002, Autor/Levy/Murnane 2003). Here, IT works as an enabler or facilitator, improving both the quality and requirements of administrative work

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[14] This substitutive effect is not at variance with the widely held hypothesis of technology-skill complementarity (e.g. Acemoglu 1998, 2002). On the contrary, this complementarity describes exactly the model's outcome (cf. below) and therefore marks just a consequence of the described substitution process (as well as of further effects related to technical change).

[15] It is important however to differentiate between wages and per-unit costs of object knowledge acquisition. Even if the latter decreases, the wage of a worker may increase if her acquired object knowledge increases to a greater extent. This seems to be perfectly consistent with the development of the wage distribution during the last decades, where low-skilled workers actually suffered a fall in real wages while the earnings of highly-skilled workers rose significantly (cf, e.g., Acemoglu 2002, Figure 2).

instead of reducing the costs of its input. The broad availability of huge amounts of data and of processing tools, for example, calls for more complex meta knowledge on the part of management, even with respect to the allocation of the very same task or the coordination of the same workers. To illustrate, whereas deciding on and instructing workers as to an ad campaign was in older days based to a large extent on the ‘business judgement’ and ‘gut feeling’ of the responsible manager, the corresponding manager is today assailed with all kinds of market data streaming from databases, data warehouse, CRM tools etc. This requires on the one hand profound analytical and statistical skills; on the other, it requires more time and cognitive capacity to arrive at a sound decision. As a result, the demand in skills (particularly those closely related to meta knowledge as, for example, analytical or people skills) have sharply risen since at least the 1970s, as have skill premia (e.g, Autor/Katz/Krueger 1998, Acemoglu 2002). This suggests that the effect of technical change on meta knowledge costs is idiosyncratic to the specific task under consideration, stymieing attempts to identify an unambiguous trend.

Communication Cost. Although the influence of technical change on communication costs seems obvious, I will even here argue that the actual impact remains somewhat ambiguous. Undoubtedly, technical developments of the last decades have significantly improved the performance of existing transmission techniques as well as led to the introduction of completely new techniques (e.g., fax, cellular phones, email, computer networks). The result has been a dramatic decrease in communication costs. Put in the right perspective, however, these unquestionable efficiency gains pertain only to the smallest fraction of overall communication costs, namely the mere transmissions costs incurred by using a communication channel (Arrow 1974). In fact, they are largely negligible compared to the sender’s costs of encoding and to the receiver’s cost of decoding and absorbing the information. Consider, for example, a briefing for the ad campaign considered in the previous paragraph. Certainly, a manager may save a few cents by sending it by e-mail instead of using the letter post. But these are “peanuts” compared to the resources (in terms of opportunity costs of her time and cognitive capacity) she spends in writing the briefing and that the addressee(s) spend(s) in absorbing and digesting its content. One could actually argue that just because there have been such significant advances in modern communication technologies over the last decades, the effective limiting (and therefore cost-driving) factor – the cognitive capacity of the human brain to absorb new information – has essentially become even more scarce and costly due to increasing channel bandwidths resulting in an overload of (frequently dispensable) information (e.g. Edmunds/Morris 2000, Eppler/Mengis 2004, Van Zandt 2004). As a consequence, the essential costs per act of communication have hardly declined; indeed, they have more probably even risen.

Worker Productivity. Technical change undoubtedly spurs improvements in the productivity of work. In fact, large parts of modern growth theory see technical progress (taken exogenously or endogenously) as one of the central drivers of lasting factor productivity growth (e.g. Solow 1957, Romer 1990), and the second crucial driver, the supply in human capital, can also be related to technical change as was argued above. Although there was initially some confusion concerning the specific impact of advancement in modern ICT as expressed in the so-called Solow productivity paradox (e.g. Triplett 1999), ample evidence has now been accumulated that corroborate the unambiguous enhancing impact of technical advancement on labor- and multifactor productivity (e.g. Brynjolfsson/Hitt 1996, 2003, Greenwood/Hercowitz/Krusell 1997, Lehr/Lichtenberg 1998).

Task Variety. A further effect of technical change is the increasing degree of specialization among firms. According to management scholars and practitioners alike, the concentration on core competencies and the outsourcing of peripheral business activities marks a major trend among firms of varied sectors and countries and is driven to a great extent by improvements in modern ICT (e.g., Powell 2001, Patel/Aran 2005, Willocks/Lacity 2006, Hecker/Kohleick 2008). The magnitude of this trend is reflected, for instance, in the tremendous growth of worldwide outsourcing markets.[16] Firm-level evidence corroborates that this trend is indeed strongly related to technical change, especially to the adoption of modern ICT (Brynjolfsson et al. 1994, Zenger/Hesterly 1997, Baumol/Blinder/Wolff 2003). Theoretical explanations for this effect hold that advancements in ICT improve the informational integration across firm boundaries and therefore lower the costs of coordinating external providers (Brynjolfsson et al. 1994). Improved ICT facilitates furthermore a better control of external providers, which in tandem with a decreasing specificity of equipment (due to the use of multi-purpose technologies) at the same time reduces cooperation hazards previously motivating vertical integration (Williamson 1979, 1985, 1991, Picot/Ripperger/Wolff 1996). Through the lens of our model, an increasing specialization among firms means a decrease in the variety of problems (Z_H) solved within a single firm. In fact, this model may even provide a framework in which the ‘core competencies’ argument becomes analytically tractable. If some of the organization’s tasks are extremely exceptional, workers responsible for them will experience much idle time (or, vice versa, incur extremely high costs of object knowledge acquisition while

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[16] According to Gartner Research (2006), the worldwide business services outsourcing market had reached an impressive volume of nearly EUR 300 billion in 2006. By 2010 it is expected to exceed EUR 400 billion.

taking on enough problems per period so as to fully utilize their working capacity). In this case, employing an expert serving multiple clients from outside the organization could be more efficient. If the costs of managing such external experts decrease due to advances in ICT, an increasing share of problems will be left to them, and the firm's size will shrink in terms of the amount and variety of internally-executed tasks.

C. Technical Change and Organizational Transformation

Merging the insights of the previous two sections, I obtain a comprehensive assessment of organizational change, integrating a number of avenues channeling the influence of technical advances. Altogether, the model's predictions on the basis of this rough but traceable analysis fit persuasively with patterns of organizational transformation actually found in reality and documented by numerous empirical studies (see Table 2).

	Impact of technical change (and corresponding developments)	Size of workforce (n)	Degree of specialization (m)	Height of hierachy (L)	Number of managers (M)	Management-to-staff-ration (M/n)
Object knowledge costs (C_{OK})	↘	→	↘	↘	↘	↘
Meta knowledge costs (C_{MK})	→	→	→	→	→	→
Communication costs (C_C)	→	→	→	→	→	→
Productivity of work ($F(Z_H)/n$)	↗	↘	↘	↘	↘	⇕
Task variety (Z_H)	↘	↘	↘	↘	↘	⇕

Table 2 Organizational impact of an increase in exogenous parameters (↗= weak increase, ↘= weak decrease, ⇕= ambiguous impact, →= no significant impact)

Regarding the organization of work, all unambiguously identified effects of technical change work in the same direction, supporting a decreasing degree of specialization in the workforce. This is highly consistent with the 'new workplace practices' (such as teamwork, broader task assignment, multitask learning or job rotation) increasingly adopted by organizations across sectors and countries (cf. section 2). This trend is accompanied by a reduction in the overall size of the workforce, which is also borne out empirically (e.g., Brynjolfsson et al. 1994, Zenger/Hesterly 1997, Baumol/Blinder/Wolff 2003). It echoes in fact three effects already discussed: the substitution of technical equipment for labor; the complementarity of technical equipment and labor, leading to increased labor productivity; and, finally, an increasing degree of specialization among firms due to improved coordination and reduced hazards of cooperation among firms. With respect to the organization of management, the flattening of hierarchies and the reduction in the number of managers is the unambiguous outcome supported by all considered channels of influence with respect to technical change. Clearly, this result also resonates well with empirical observations (cf. section 2).

In this vein, the model reconciles the apparent contradiction that technical change – and particularly improvements in ICT – should facilitate coordination and thus foster specialization and greater centralization, as according to theoretical predictions, but in fact gives rise to organizational patterns reflecting a lower degree of specialization and more decentralized decision making. It therefore actually provides a solution to the puzzle described at the outset. Key is the insight that technical change exerts influence through a number of channels and at different loci within organizations. Any 'black-box'-type analysis that fails to provide for the multitude of effects unpacked above (and that, say, considers only effects on communication costs in mere terms of transmission costs or undifferentiated costs of knowledge acquisition) inevitably falls short of effectively coping with the problem's inherent complexity.

Although a comparative assessment of the relative strength (or marginal contribution) of different effects is not possible, owing to the general nature of the model's design, the outcomes nonetheless seem rather robust in light of the sheer number of aligned effects. Even if evidence suggested, for example, a decrease in communication costs more pronounced than admitted above, the predicted organizational patterns would remain stable for a wide range of possible specifications. Of course, the concrete appraisal of such specifications as well as the estimation of actual parameter changes due to technical change must be relegated to further empirical examination.

V. Conclusion

In developing a fresh and augmented approach to analyze the organization of knowledge within firms, this paper pursues two aims. On the one hand it sheds light on the raison d'être and efficiency properties of some widespread organizational patterns such as hierarchies. On the other hand, it provides a differentiated account of the transformational forces working on these organizational patterns driven by technical change. In conclusion, I will point to some limitations and, accordingly, to some avenues for future research. A first point I have already mentioned in the previous section. While the model's rather general design guarantees the generality of the results obtained, it defies at the same time a comparative assessment of the relative strength (or marginal contribution) of different effects. As a more concrete specification from the drawing board would be arbitrary, empirical research is required to calibrate the model. This also holds for sound estimations of actual parameter changes due to technical advance. Such empirical work would provide the basis for an ultimate test of the explanatory and predictive power of the approach introduced here.

Furthermore, while the model advances alternative approaches by allowing for multifaceted forms of specialization (e.g., horizontal vs. vertical specialization, managers vs. experts vs. line workers), the simplifying assumption of homogeneity with respect to workers' and managers' talent or learning aptitude constitutes another limitation. Accordingly, a straightforward extension of the model would consist of incorporating talent as a further parameter, specifying the knowledge acquisition cost function. Such an extended model would exhibit a number of favorable properties. Under common scarcity constraints on talent, it would for example exhibit positive assortative matching, meaning that the hierarchical rank of a manager would increase with her talent in an efficient organization, whereby we arrive at the CEO as the most talented person. The same would be true for workers, where the exceptionality of tasks increases with talent such that the most specialized experts are endowed with the greatest talent. Such a model could thereby account for wage differentials between hierarchical levels or between ordinary workers and experts respectively.

This latter aspect points broadly to a promising direction for future research. As already mentioned, knowledge acquisition costs are closely related to wages for persons of differing training and talent. It therefore stands to reason to link the model's results to the prominent debate about skill-biased technological change (cf. the surveys Aghion/Caroli/García-Penalosa 1999 and Acemoglu 2002). For example, and to give a flavor of such a kind of extension, the increasing demand for object knowledge per worker as predicted by the model could shed light on an intriguing puzzle in this debate, namely on the decline in real wages of low-skill workers (cf. Acemoglu 2002, p. 44). A further way of elaboration would consist in integrating this organizational model into an equilibrium framework, in which both the organizational and the wage structure (i.e. costs of object and meta knowledge acquisition) are endogenously determined. Within such a model, questions of high practical and political relevance could be addressed, such as questions related to the impact of improvements in ICT (with the potential for very fine-grained analysis integrating a number of channels and mechanisms of impact) on both organizational form and the distribution of earnings.

Appendix

PROOF OF PROPOSITION 1. Ad a) An arrangement of managers may be any pattern of linkages in terms of meta knowledge and communication among them. To characterize the arrangement in which matching costs (i.e. the sum of meta knowledge and communication costs) are minimized, consider that a manager's meta knowledge assigns her a set of workers and/or managers to whom she is able to delegate tasks, and conceive this as a 'superior-to' relation employed in building up a hierarchy. To actually obtain a full-fledged hierarchy, i.e. a ranked tree, this relation must exhibit further properties: (i) transitivity; (ii) anti-symmetry; (iii) exactly one manager is superior to all other managers and workers; (iv) the number of immediate superiors (except for this top manager) is restricted to exactly one (Radner 1992, 1993). It is easy to show that these restrictions hold for efficient arrangements of workers and managers in the case of top-down problem allocation: By definition there is one manager 'at the helm' navigating problems - the top manager as required by (iii) - who refers emergent problems to appropriately skilled workers, usually by way of further managers. These managers thus constitute an unambiguous chain of referral satisfying (i) and (ii). The last restriction (iv) is justified by efficiency considerations: Efficient top-down problem allocation obviously requires exactly one path from the top manager to each worker, as a second path would increase the required meta knowledge without adding any value (e.g. in terms of economizing communication costs). Finally, it is immediate that in an efficient arrangement there is a one-to-one correspondence between meta knowledge and communication linkages. ■

Ad b) To prove the second part of the proposition by contradiction, note first that all managers are subject to the same meta knowledge cost function and thus, ceteris paribus, will exhibit the same optimal span of control. It is therefore sufficient to exclude the contradicting case that in an efficient hierarchy a manager is assigned to a new level before the preceding level is completely filled by managers. Suppose that there is a manger supervising s_{i+1} workers assigned to a superior who herself exhibits a span of control s_i while there is still at least one worker assigned to the level of the superior. Then the organization can economize communication costs in the amount of $(s_{i+1}-1)/n \cdot C_C$ and meta knowledge acquisition costs amounting to $C_{MK}\left(\frac{s_i+s_{i+1}-1}{n}\cdot Z_H, s_i\right)-C_{MK}\left(\frac{s_i}{n}\cdot Z_H, s_i\right)$ by exchanging this manager for the worker at the preceding level; it cannot therefore be efficient.[17] ■

Ad c) Let s_i denote the span of control and M_i the number of managers of level $i\in\{1,\ldots,L\}$ where 1 denotes the top and L the bottom hierarchical level. Suppose there is a hierarchy such that for two adjacent levels $s_i > s_{i+1}$ holds. Then by exchanging s_i for s_{i+1}, the organization can economize meta knowledge acquisition costs in the amount of

$$M_i\cdot\left(C_{MK}\left(\frac{Z_H}{M_i}, s_i\right)-C_{MK}\left(\frac{Z_H}{M_i}, s_{i+1}\right)\right)-s_{i+1}\cdot M_i\cdot C_{MK}\left(\frac{Z_H}{s_{i+1}\cdot M_i}, s_i\right)+s_i\cdot M_i\cdot C_{MK}\left(\frac{Z_H}{s_i\cdot M_i}, s_{i+1}\right),$$

which, by the definition of the meta knowledge cost function, is positive. This organization cannot therefore be efficient. ■

PROOF OF PROPOSITION 2. Ad a) That (and how) exactly one specific hierarchy minimizes (and in some borderline cases maximally two hierarchies minimize) matching costs C^M as the sum of meta knowledge acquisition costs C^{MK} and communication costs C^C can most easily be seen by considering the basic construction principles of such a hierarchy. Let us start, therefore, with small n=1, 2, 3, … and see how the optimal hierarchy develops with increasing n. For small n, the optimal hierarchy for top-down problem matching is certainly of a single manager who allocates all problems to the n workers. With the per period number of total problems to be allocated $F(Z_H)$ normalized to 1, this manager incurs matching costs of

$$C^M(n)=C_{MK}(Z_H,n)+C_C. \tag{8}$$

As $C_{MK}(Z_H,n)$ increases disproportionately in n, at some point it will prove more efficient to employ a second manager on a second hierarchical level, amounting to matching costs of

$$C^M(n)=C_{MK}(Z_H,n-1)+C_{MK}\left(\frac{2}{n}\cdot Z_H,2\right)+\left(1+\frac{2}{n}\right)\cdot C_C. \tag{9}$$

As hinted above, the optimal hierarchy is determined by optimizing the trade-off between the costs of meta knowledge acquisition and communication. Strictly speaking, a hierarchy with two instead of just one manager will be more efficient iff

$$C_{MK}(Z_H,n)-C_{MK}(Z_H,n-1)-C_{MK}\left(\frac{2}{n}\cdot Z_H,2\right)>\frac{2}{n}\cdot C_C \tag{10}$$

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[17] Without loss of generality I normalize the per period of problems to unity, i.e. set $F(Z_H)=1$, throughout.

(and in the borderline case, (10) holds such that both hierarchies are equally efficient). That there is in fact some n above which (10) holds is assured by the fact that the left part of (10) increases in n - given the convexity of $C_{MK}(Z_H, n)$ - whereas the right part decreases. In the same manner, a further increase in n will at some point call for a third manager, and so on. At this point there are actually two different ways of enhancing the hierarchy, either by 'filling up' the second hierarchical level or by establishing a third level. However, from proposition 1b) we know that the latter means cannot be efficient. A long these lines, we can construct for every n a matching cost-minimizing hierarchy, which is determined in terms of the optimal number of managers (M), the height of the hierarchy (L), and the optimal span of control s_i for each hierarchical level $i \in \{1,\ldots,L\}$ whereby M, L and the average span of control $\overline{s}$ evidently (weakly) increase in n. ■

Ad b) Matching costs combine meta knowledge acquisition costs and communication costs, i.e. $C^M(n) = C^{MK}(n) + C^C(n)$. $C^{MK}(n)$ sums up meta knowledge acquisition cost for each manager on each hierarchical level $i \in \{1,\ldots,L(n)\}$, where 1 denotes the top and L(n) the bottom level. L(n) is implicitly determined by

$$\prod_{i=1}^{L} s_i = n \tag{11}$$

where s_i refers to the span of control of level i. The product $s_1 \cdot s_2 \cdot \ldots \cdot s_{i-1}$ accordingly yields the number of managers in level i. Meta knowledge acquisition costs then amount to

$$C^{MK}(n) = C_{MK}(Z_H, s_1) + \sum_{i=2}^{L(n)} \left(\prod_{j=1}^{i-1} (s_j) \cdot C_{MK} \left(\frac{Z_H}{\prod_{j=1}^{i-1} s_j}, s_i \right) \right). \tag{12}$$

$C^C(n)$ on the other hand is simply determined by the height of the hierarchy and is given by

$$C^C(n) = L(n) \cdot C_C.^{18} \tag{13}$$

To see that $C^M(n)$ is approximately a (weakly) concave function in n, consider that $C^{MK}(n)$ is approximately a (weakly) concave function in n since the range of problems with which a manager on level i must deal (Z_H/M_i) decreases for every newly established hierarchical level. These economizing effects on $C^{MK}(n)/n$ will not be overcompensated by a possible increase

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[18] Of course, this notation of communication costs neglects integer constraints and presumes that level L is filled by managers and that no workers are left remaining at this level. If, owing to integer constraints, that is not the case, (7) marks only an upper bound of communication costs.

in the span of control.[19] At the same time $C^{C}(n)$ is a (weakly) concave function in n as the height of the hierarchy L increases in n on a diminishing scale. Then $C^{M}(n)$, as the sum of both, is also approximately a (weakly) concave function.[20] ■

PROOF OF PROPOSITION 3. To prove this proposition I show in a first step that object knowledge acquisition costs as given by (4) constitute a convex decreasing function of m, i.e. with respect to integer constraints, that $C^{OK}(m-1)-C^{OK}(m)>0$ and $2\cdot C^{OK}(m)\leq C^{OK}(m-1)+C^{OK}(m+1)$. Let us denote by n_i the number of workers of shop i. Reducing m by 1 means that one shop is 'closed' and its workers are uniformly redistributed to the $m-1$ remaining shops, which now cover the requisite object knowledge Z_H. Assuming that shop $a\in\{1,\dots m\}$ is 'closed' and denoting the additional object knowledge covered by shop i ΔZ_i, we can write

$$\begin{aligned}&C^{OK}(m-1)-C^{OK}(m)=\\&\sum_{i\in\{1,..,m\}\setminus\{a\}}\left(C_{OK}(Z_i-Z_{i-1}+\Delta Z_i)\cdot\left(n_i+\frac{n_a}{m-1}\right)-C_{OK}(Z_i-Z_{i-1})\cdot n_i\right)-C_{OK}(Z_a-Z_{a-1})\cdot n_a,\\&\quad\text{such that } Z_i=F^{-1}\left(\frac{i\cdot F(Z_H)}{n}\right)\text{ and }\sum_{i\in\{1,..,m\}\setminus\{a\}}\Delta Z_i=Z_a-Z_{a-1}.\end{aligned}\tag{14}$$

Since $C_{OK}(\cdot)$ was defined as convex function, this difference is certainly positive, which proves that $C^{OK}(m)$ is monotonically decreasing in m. To see that it is also convexly decreasing, consider that the size of the difference as given by (14) depends on the amount of object knowledge covered by the 'closed' shop as well as by the remaining shops, i.e. more precisely that $C^{OK}(m-1)-C^{OK}(m)$ increases with Z_a-Z_{a-1} as well as with $Z_i-Z_{i-1}, i\in\{1,..,m\}\setminus\{a\}$. Z_a-Z_{a-1} and Z_i-Z_{i-1}, $i\in\{1,..,m\}\setminus\{a\}$, are in turn decreasing functions in m, as the amount

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[19] More precisely, increasing n by one can have two possible effects: (i) the span of control of an existing manager increases, resulting in a locally convex increase of $C^{MK}(n)$; (ii) a new manager is deployed on an already or newly established level, resulting in a (weakly) concave increase of $C^{MK}(n)$. As the range of problems with which a manager on level i has to deal (Z_H/M_i) decreases from level to level, the second effect will clearly prevail in the long run, which is meant by characterizing $C^{MK}(n)$ as approximately (weakly) concave.

[20] An alternative way of proving the approximate (weak) concavity of $C^{M}(n)$ is to consider a uniform hierarchy with a unique span of control $\hat{s}$. The height of such a hierarchy can be approximated by $L(n)=\log_{\hat{s}} n$. Plugging this into $C^{M}(n)$ as given by (3) clearly yields a concave function. As the matching costs of such a hierarchy can be seen by proposition 1 as an upper bound on the matching costs of the actual efficient hierarchy (which may exhibit varying spans of control on different hierarchical levels), the latter must at least constitute approximately a concave function as well.

of object knowledge covered by a shop strictly decreases in the overall number of shops. $2\cdot C^{OK}(m)\leq C^{OK}(m-1)+C^{OK}(m+1)$ therefore holds.

On the other hand it was shown in the proof of proposition 2 that matching costs $C^{M}(m)$ constitute approximately a (weakly) concave function in m. Accordingly, there exists a m^{*} that minimizes the production costs $C^{P}(m)$ as the sum of $C^{OK}(m)$ and $C^{M}(m)$. More specifically, we can distinguish a number of cases:

Case		**Optimal degree of specialization**
A	$\forall m\in[1,n-1]:C^{OK}(m)-C^{OK}(m+1)+C^{M}(m)-C^{M}(m+1)>0$	$m^{*}=n$
B	$\forall m\in[1,n-1]:C^{OK}(m)-C^{OK}(m+1)+C^{M}(m)-C^{M}(m+1)<0$	$m^{*}=1$
C	$\exists m_0:\forall m\in[1,m_0-1]:C^{OK}(m)-C^{OK}(m+1)+C^{M}(m)-C^{M}(m+1)>0$ $\wedge\forall m\in]m_0,n-1]:C^{OK}(m)-C^{OK}(m+1)+C^{M}(m)-C^{M}(m+1)<0$[21]	$m^{*}=m_0$
D	$\exists m_0:\forall m\in[1,m_0-1]:C^{OK}(m)-C^{OK}(m+1)+C^{M}(m)-C^{M}(m+1)<0$ $\wedge\forall m\in]m_0,n-1]:C^{OK}(m)-C^{OK}(m)+C^{M}(m)-C^{M}(m)>0$	$m^{*}\in\{1,n\}$

Table 3 Optimal degree of specialization m^{*} depending on the curvature of $C^{OK}(m)$ and $C^{M}(m)$

$C^{M}(m)$ reflects the matching costs of that hierarchy for a given m, which in turn optimizes the trade-off between meta knowledge acquisition and communication costs (cf. proposition 2a). This assigns to each m^{*} an optimal hierarchy in terms of the optimal the number of managers (M), the height of the hierarchy (L), and the optimal span of control s_i for each hierarchical level $i\in\{1,\ldots,L\}$. ■

PROOF OF PROPOSITION 4. A decrease in C_{OK} - i.e. the multiplication of $C_{OK}(\cdot)$ by a scalar factor smaller than one - will lower $C^{OK}(m)-C^{OK}(m+1)$ for all m. Referring to the case differentiation in Table 3, a decreasing C_{OK} consequently leads to a (weakly) decreasing m_0 in case C on the one hand and to more and more former instances of case A switching to case C on the other; the other cases remain untouched. Altogether, the result is a (weak) decrease in the optimal degree of specialization (m^{*}) and, accordingly, in the number of managers

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[21] If there are multiple inflection points where $C^{OK}(m)-C^{OK}(m+1)+C^{M}(m)-C^{M}(m+1)$ changes its sign then m^{*} is evidently determined by the global optimum.

(M), the management-to-staff ratio (M/n) and the height of the hierarchy (L)(cf. hypothesis 2a). ■

PROOF OF PROPOSITION 5. A decrease in C_{MK} - the multiplication of $C_{MK}(Z,s)$ by a scalar factor smaller than one – affects the trade-off between object knowledge acquisition and matching costs as well as the trade-off between meta knowledge acquisition and communication costs. With respect to the first, it raises $C^M(m)-C^M(m+1)$ for all m. Referring to the case differentiation in Table 3, a decreasing C_{MK} consequently leads to an increasing m_0 in case C and to more and more former instances of case B switching to case C; again, the other cases remain untouched. Altogether, the result is a (weak) increase in the optimal degree of specialization (m^*) and, accordingly, in the number of managers (M), the management-to-staff ratio (M/n) and the height of the hierarchy (L)(cf. hypothesis 2a). Regarding the trade-off between meta knowledge acquisition and communication costs, a decrease in C_{MK} will lower the costs of an increase in the span of control while the resulting savings of communication costs remain the same, which pushes each hierarchical level - at least if integer constraints permit - to a larger span of control. Such an effect has a decreasing impact on M, M/n and L. On balance, a decrease in C_{MK} leads to a (weak) increase in the optimal degree of specialization (m) but has an ambiguous effect on the number of managers (M), the management-to-staff ratio (M/n), and the height of the hierarchy (L). ■

PROOF OF PROPOSITION 6. A decrease in C_C affects the trade-off between object knowledge acquisition and matching costs as well as the trade-off between meta knowledge acquisition and communication costs. With respect to the first, it raises $C^M(m)-C^M(m+1)$ for all m. Referring to the case differentiation in Table 3, a decreasing C_C consequently leads to an increasing m_0 in case C and to more and more instances of case B switching to case C, whereas the other cases remain untouched. Altogether, the result is a (weak) increase in the optimal degree of specialization (m^*) and, accordingly, in the number of managers (M), the management-to-staff ratio (M/n), and the height of the hierarchy (L) (cf. hypothesis 2a). Regarding the trade-off between meta knowledge acquisition and communication costs, a decrease in C_C will lower the savings from an increase in the span of control while the mark-up of meta knowledge acquisition costs stays the same, which pushes each hierarchical level - at least if integer constraints permit - to a smaller span of control. This further amplifies the effects on M, M/n and L. ■

PROOF OF PROPOSITION 7. An increase of each worker's productivity (or equivalently capacity) is equivalent to an increase in $F(Z_H)/n$, which immediately implies a decrease in the overall workforce (n) as the amount of problems to be solved $F(Z_H)$ remains constant. At the same time, the amount of object knowledge to be acquired by each worker increases, implying a decrease of $C^{OK}(m) - C^{OK}(m+1)$ for all m. By analogy to the proof of proposition 4, this results in a (weak) decrease in the optimal degree of specialization (m^*), in the number of managers (M), and the height of the hierarchy (L). But as n decreases at the same time, the impact on the management-to-staff ratio (M/n) is ambiguous. ■

PROOF OF PROPOSITION 8. Subject to a given problem distribution $F(Z)$ and to a fixed capacity constraint of workers $F(Z_H)/n$, an increase in Z_H implies an increase in the overall workforce (n) as well as in the cost of object knowledge acquisition. At the same time $C^{OK}(m) - C^{OK}(m+1)$ increases due to the convexity of C^{OK}, implying – by analogy to the proof of proposition 4 – a (weak) increase in the optimal degree of specialization (m^*), in the number of managers (M), and the height of the hierarchy (L). But as the ratio of the increases in n and M remains uncertain, the impact on the management-to-staff ratio (M/n) is ambiguous. ■

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