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Werner Hölzl & Andreas Reinstaller

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MERIT – Maastricht Economic Research Institute on Innovation and Technology

PO Box 616
6200 MD Maastricht
The Netherlands
T: +31 43 3883875
F: +31 43 3884905

http://meritbbs.unimaas.nl
e-mail:secr-merit@merit.unimaas.nl

International Institute of Infonomics

c/o Maastricht University
PO Box 616
6200 MD Maastricht
The Netherlands
T: +31 43 388 3875
F: +31 45 388 4905

http://www.infonomics.nl
e-mail: secr@infonomics.nl

The Babbage principle after evolutionary economics

Werner Hölzl and Andreas Reinstaller[♣]

Abstract

In this paper we analyse the cognitive roots of the division of labour and relate it to the reduction of tacitness in the organisation and technology of a firm. We study the interaction between efforts of knowledge codification and problems of control in production from an evolutionary and complex systems perspective. By applying our framework to the emergence of white-collar work in the late 19th century and the modern knowledge economy we assert that property rights and limits to codification of knowledge are important forces shaping the process of organisational and technological change.

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1 Introduction

Marx linked labour displacing technical change to the capitalist mode of production, where the ownership of the means of production and the historical conditions of production are reflected in the organisation of production. He identified the manufacturing division of labour (Babbage principle) as a main instrument of power in the hands of capitalists leading to the deskilling of workers and the development of machinery embodying their knowledge. Numerous contributors to the labour process literature have pursued and affirmed Marx's perspective. Braverman (1974) stressed the importance of the Babbage principle in relation to the rise of a white-collar working class. His study underscored the role "divide and rule" had in implementing the economic interests of capitalists and in deskilling and displacing clerical workers through the mechanisation of office work. Glenn and Feldberg (1979) came to a similar conclusion for the case of the introduction of early electronic computers in the modern office. In a recent paper Hecht (2001) has further corroborated this view by finding that labour displacing technical change was a persistent feature in the insurance industry in post-war USA. A number of studies on the rise of modern accounting have advanced the thesis that accounting controls established round the turn of the 19th to the 20th century, and the rise of large administrative machineries along with them, were not a consequence of economic or technological imperatives, but rather were rooted in struggles as managers attempted to control labour processes (Hopper and Armstrong, 1991; Bhimani, 1993; Bhimani 1994). Labour deskilling and displacement in the office is viewed as the outcome of a process of class struggle and of the aim of capitalists to construct a "governable person" (Miller and O'Leary, 1987). The question whether the labour displacement resulting from the application of the Babbage principle is the *result* of a process of searching for solutions to problems given by historical conditions or whether it is primarily an *instrument* of capitalists to gain power and control over workers has not found much consideration. In most studies it is posited that it is a principle inherent to power and thus also inherent to the social class which has control over the means of production. Furthermore, the limits of this process of appropriation are not analysed. Not all skills or knowledge are equally suited to being transformed into technological blueprints in such a way that enables the replacement of workers with machines.

The deskilling argument put forward in the labour process literature can be interpreted as the result of a process of codification of knowledge and extraction of human capital that is, skills and tacit knowledge from workers.[1] The issue of tacitness of knowledge in production and codification has featured prominently in the evolutionary critique of Neoclassical theories of technical change. However, evolutionary economists have viewed codification, tacitness and appropriation mainly as an issue relevant for the competitive advantage of firms (e.g. Saviotti, 1998) and have not tried to relate it to issues of control over the labour process. Evolutionary economists contend that if firms are not able to appropriate their technological knowledge it will spill over to competitors, who will catch up and weaken their competitive position. In order to maintain their competitive advantage they must try to push forward their technological frontier faster than knowledge leaks. Only a few contributions have studied the process of codification (e.g. Hippel and Tyre, 1995; Cowan and Foray, 1997), and to the knowledge of the authors of this paper no work has addressed the issue of appropriability of knowledge and the distribution of knowledge between firms and workers in detail. This question is insofar of interest as its analysis sheds light on the inducement mechanisms fostering the effective extraction and recombination of organisational and technical knowledge.

Cowan and Foray (1997) have emphasised that the codification of knowledge involves three distinct but related aspects: the creation of (mental and heuristic) models solving a given problem, the creation of languages enabling the description of the problem and solutions and the creation of messages describing the problem or solutions for it. From this they conclude that codification entails the creation of new knowledge. Nelson and Winter (1982) refer to incentives in their discussion of the codification of knowledge, when they say that

[1] Throughout this paper we follow the definition of tacitness and codification given in Cowan, David and Foray (2000).

"circumstances place a great premium on effective articulation, remarkable things can sometimes be accomplished", (p. 78). But eventually they remain on neutral grounds when they find that it is mostly a matter of cost (p.80). Cowan, David and Foray (2000) take up this stance and argue that very little knowledge is inherently tacit and impossible to codify and whether codification takes place or not is essentially a question of costs and benefits. However, a treatment of inducement mechanisms in firm level technical change that goes beyond the traditional cost argument is not advanced.

In this paper we assert that problems of control creating imbalances in the production system act as important focusing devices in the process of codification and creation of new knowledge on the firm level. We analyse the interaction between efforts of knowledge codification and problems of control in production. We establish that control over production is increased in a modular design of the activities of a firm and that this is an outcome of problem decomposition and the search for new organisational and technological routines. The importance of activities coordinating the interaction of other activities increases. This does not necessarily favour the appropriation of knowledge by firms but may also increase the relative power of individuals who have acquired critical knowledge on how to mediate between elements of the firm. We show that this is reflected in the technological and organisational designs emerging out of this process. We advance a historical case study on the development and implementation of modern office work in the period between 1870 and 1930 in order to discuss our theory on an empirical level to this end. Final remarks and prospective considerations on the role of knowledge appropriation in the "knowledge economy" conclude our paper.

2 The cognitive roots of the Babbage principle

2.1 Technology and the organisation of the firm

A central concept in evolutionary economics is the idea that technological search conceived as problem solving activity develops along trajectories predetermined by technological paradigms. These technological paradigms are models of solution for selected problems, are based on selected material technologies and have a powerful exclusion effect in the sense that they are cognitive focusing devices in terms of the possible directions of search and the perception of technological possibilities (Dosi, 1982, p. 152-3). On the other hand Nelson and Winter (1982) stressed that routines are the basis for any economic organisation. Routines are present in technological search and in the organisation of productive activity. They are the result of past learning efforts in the realm of a specific technological paradigm and constitute the organisational memory of a firm. As such they are embodied in and link activities with the aim of producing goods or processing information.

The selection environment of the firm ulitimately shapes the resulting organisation of production by constraining the space of possible options of choice and behaviour. Factors external to the firm are therefore important to understanding its internal set up. Firms are embedded in a specific institutional environment (see Coriat and Dosi, 1998), which influences the regional or sectoral innovation system of a firm as well as the social norms determining consumer choices. Yet, the most important and pervasive factor is the dominant property rights regime. It affects the costs of a firm insofar as it influences the wage bargaining mechanism, but it also establishes the type of control that management has to exert over production. To this extent, property rights have a direct impact on the organisational and technological designs that will emerge from technological search.

The systemic perspective we adopt to analyse the influence of property rights on the structure of a firm and the design of adopted technologies is similar to the one proposed by Potts (2000). We view production and organisation as linked elements (activities) that make up the structure of the firm. This structure provides (i) the competence to process inputs into outputs and (ii) the competence to make further connections. We will analyse this structure in order to better understand how appropriation from economic activity and technological search works and shed light on the principles underlying the Babbage “divide and rule” heuristic.

2.1.1 Property rights in technological and organisational change

Property rights are central institutional elements in any economy. They confer to the holder the right to select the use of an economic good. Their value lies in the pattern of resource management they promote. Of course, property rights are far from perfect. The costs of enforcement and the probability of alienability define their strength. Under capitalism, physical property and the pooling of capital into going concerns with limited liability are strong, while rights on intangible assets are much weaker. This makes the allocation of economic property rights an important ingredient in the shaping of the direction of technical and organisational change.

First, the capitalists’ right to a reward for advanced capital requires the enforcement of operating routines on the level of the organisation and technology of a firm in order to assure a return for their investment. The task of the management of a firm is to coordinate and organize production activities on behalf of the owners. For this purpose it is necessary that management be able to identify deviations. Accounting systems and reporting systems deliver the information needed to detect deviations from the objective. Thus, property rights and entrepreneurial activity define the form of the effective organisation of the firm, as there is an incentive to implement organisational measures and favour technological designs that support control.

The second influence property rights exert on technical and organisational change derives from the fact that property rights are not perfectly enforceable. Nonaka (1994) has devised a theory according to which organisational knowledge is created through a continuous dialogue between tacit and codified knowledge that gives rise to a virtuous spiral in which individuals codify and share their knowledge with other members of the organisation, acquire new tacit knowledge and share that again. Nonaka’s theory does not discuss the fact that the presence of tacit knowledge clearly implies a lack of control for the owners of a firm. Hence, there is an incentive to reduce the tacitness of production activities.

2.1.2 The firm as a complex system: complementarity, complexity and technological paradigms

The structure of a firm is a more or less complex network in which the products of one activity, such as physical (final or intermediate) goods or information, are the inputs of another. Some of the ties in this web can be very strong, while others may be weaker. Their strength can result from strict technical complementarities, which are static, but also from dynamic complementarities, which capture learning spillovers, synergy effects and other mechanisms generating dynamically increasing returns.

A useful metaphor for thinking about complex systems is Stuart Kauffman's NK model (Kauffman, 1993). The NK model is extremely simple, it presents a system with N elements, each of which can take one of x possible states, and K dependence relations between these elements. The NK model can easily be thought to represent a production system with N production activities. If an activity is not linked to any other activity then we have the constellation of perfect separability, which is implicit in Neoclassical production functions. Under perfect separability each activity can be changed or even exchanged without compromising the working of the system, as the performance of other elements is not influenced. However, if an element is interdependent with other activities in the network, then its removal may affect the performance of the other activities. Centralised control is highest, when the network is separable, and lowest with complete interdependence.

[Figure 1 about here]

This can be visualised by means of a generalised NK representation (Altenberg, 1997) presented in figure 1, with N (activities) = 3 and K (output characteristics) = 3. The technical characteristics capture the production side of a firm and its link to science and technology. The service characteristics instead capture the link of the firm to the external environment and especially its demand, as products are bought for the services they deliver (Saviotti and Metcalfe, 1984, Saviotti, 1996, pp. 63, Frenken, 2001). The matrices map technical characteristics of activities into service characteristics; they capture the internal structure of the firm. For example figure 1a) shows a matrix where each column represents an activity and each row gives the Lancasterian service characteristics C_1 -C_3 of the final product which they influence. The value of each characteristic is the sum of the contribution of all activities (I_i) having an influence on it. A single activity may affect one or several output characteristics and single output characteristics may be affected by one or several activities. Each activity contributes to the competitiveness of the firm. The total performance is calculated as the average over the performance contribution of every activity. The single activities are in turn assumed to be linked through standardised channels of communication in the spots where there are overlaps in the contribution to an output characteristic. One may think of different departments of a firm, which are related to each other through a standardised flow of information. Hence the matrices in figure 1 are graphical representations of near-decomposable systems (e.g. Simon, 1996): the activities have high interdependence with the output characteristics and low (and standardised) interdependence amongst themselves.[2]

Following Saviotti and Metcalfe (1984) radical innovation leads to a new internal structure of the firm and new service characteristics. An incremental innovation instead improves the service characteristics over time with minor changes in the internal structure of the firm. An example of incremental change in service characteristics is the car. Its blueprint has been in place for a long time and the basic underlying technological idea has not changed for a hundred years. No firm entering the market at a later time needed to invent the basic concept of the car from scratch. The central technical characteristics have remained constant over time, while much improvement has taken place in its output characteristics such as speed or security.

Some activities will mediate the interaction between other activities and in this way influence the output characteristics. These may be viewed as the "core" of the evolving organisation and technology of a firm. Figure 1b) provides an example where activity $I_{1'}$ forms such a core (see Frenken, op.cit.). If no such activities would exist then the firm would just be a collection of unrelated organisational and technological processes no interacting with each other. Activities affecting many output characteristics simultaneously are critical, as a change may affect the performance of the firm to a larger extent than activities influencing only one isolated output characteristic. They lower the control of the management over the competitiveness of the firm because a small change may have large effects. This result has been presented in a genetic context by Altenberg (1995). His simulation study found that lower performance values are likely to be associated with activities affecting many output characteristics, because for these the probability of having dismal effects on overall performance is higher. At the other extreme, an activity affecting only one characteristic is likely to show higher contributions to overall performance, as negative changes do not have a pervasive effect and can be identified and isolated without affecting other output characteristics. A technology map consisting only of such activities is perfectly separable (and modular) and would maximise control of management, but it is devoid of a coordination mechanism relating them to each other. Here, it would no longer be possible to talk about a firm.

[2] For a more exhaustive discussion of the generalised NK model and its relation to Kauffman's model the reader is referred to the papers by Frenken (2001, 2002) and Frenken, Marengo and Valente (2002).

The existence of highly interrelated activities has two implications on the process of innovation and technological search. First, the discussion in the previous paragraph suggests that for core activities more trade-offs between the performance values of different functions exist, as the probability that the improvements in performance of some functions are offset by reductions in performance of other functions is higher. The more complex the process technology, the higher is the likelihood that a change in one component may conflict with the overall performance. This implies that elements in the "core" are less likely to be changed. Improvements within the context of a technological paradigm take place mostly by substituting, adding or changing activities that are peripheral, such as inputs I_2 and I_3 in figure 1 b). The second implication is that it represents a stable and profitable set-up and reduces technological uncertainty (Caminati, 1999). The "core" represents a design of a process technology that works and that can be further explored, as the example of the car suggests. Usually there is an incentive to keep the "core" elements of the operating techniques as they are. If external shocks punctuate the evolutionary equilibrium (e.g. shifts in customer preferences or sudden and persistent rises in prices of some inputs) the strong complementarities in the "core" may turn into binding constraints by causing imbalances between activities and hindering adaptation. Then firms have an incentive to break up the constraint posed by complementarities between the different elements of the "core". In this way complementarities become focusing devices for organisational and technical change.

2.2 Problem solving, learning and appropriability

The competitive position of a firm does not only depend on how well it has adapted its different capabilities to a given environment at a given point in time, but also on how well it is able to adjust to or bring about changes in the future (see Metcalfe, 1998, p. 86 ff). In terms of the NK model presented earlier, adaptability means a firm's capability of establishing new linkages and breaking up existing ones. In a dynamic environment this is an extraordinarily important capability. Unpredictable innovation behaviour of competitors requires a high adaptability, i.e. the capacity to change the operating rules and routines of the firm.[3] The organisational and technological routines of a firm reflect solutions to a given economic coordination problem. As such they filter, condense as well as interpret information and enforce guidelines imposed in order to achieve a targeted performance (Arrow, 1974). Changes in the environment will be perceived when the performance is negatively affected, and the organisation has routines to detect such deviations. They indicate a situation where its organisation or its technology is not able to perfectly handle the problem. In a complex system, where it is difficult to detect clear causalities, this implies a loss of control. In these situations the appropriation of yields from economic activity works imperfectly. Loss of control means that existing routines and heuristics have a limited capability to handle the problem. Thus there is an incentive to engage in an activity of generating routines, which we may conceive as new (mental and procedural) models, languages and signals, which are adapted to the new situation. Firms will try to generate new rules or adapt existing ones to the new circumstances and to integrate them into the texture of rules and heuristics that are not under pressure. If the firm fails in this process, this may lead to its exit from the market. This is not unlikely, as the process of search is difficult because it is difficult to detect causalities in complex networks, which is achieved – as will be argued - by modularising the activity of production.

2.2.1 Problem decomposition

An event external to the firm or the failure of an extant routine or heuristic may trigger the creation of new rules, if the given system of routines is not able to handle the change. The first step in this direction is to gain an understanding of the problem through its cognitive decomposition into its constituting elements. If this principle is applied on activities of a firm or

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[3] In this regard concepts like absorptive capacities (see Cohen and Levinthal, 1989) and dynamic capabilities (Teece and Pisano, 1994) have been studied in relation to rules related to innovation and organization.

larger ensembles of them a complex system is transformed into a modular one. Decomposition leads to the break down of a system into its constituting elements leading to an understanding and codification of the properties of its single parts and of their laws of interaction. This allows the control over its operation to be increased.

Learning and decomposition takes place through the detection of co-variation between changes in elements of the system (Holland et al., 1986, p. 151 ff.). Clear causalities for such co-variations are to be discovered only if building blocks of the system are identified whose values can be computed independently of other elements of the system (Simon and Ando, 1961; Iwasaki and Simon, 1994). From these the interactions of subsystems, and their effects on the objective function of the firm follow. It is thus a fundamental feature of every problem solving process to break a problem down into its constituting elements. This is true for the division of labour as well as for the innovation process (von Hippel, 1990; Nelson and Nelson, 2002). Problem decomposition is a hierarchical process. It is the art of the person engaged in the solution of a problem to think about where it is *not* necessary to search – this is the talent of the entrepreneur. It is (cognitively) impossible to find a solution in a set with an infinite number of possible outcomes. Co-variation detection and cognitive framing help. Cognitive framing groups different consistent behavioural patterns into subsystems. It is straightforward to distinguish production activities from administrative ones, or to distinguish activities of assembly from activities of moulding product components. It is a first step to make sense out of a complex system. It allows identifying subsystems where problems occur. Co-variation detection is the cognitive capability to recognise correlated changes in a system. It is most accurate for events or event relations that are visible, i.e. for relations where large changes in the organisation of work also cause large changes in the performance of the firm, or put in a different way, where there is "strong causality" (see Holland et al., 1986, p. 176). If this is the case, then it is relatively easy to delimit the problem and start searching for a path towards a better solution and new routines through a process of vicarious trial and error (e.g. Campbell, 1987; Vincenti, 1990; von Hippel and Tyre, 1995). From its very beginning the interaction of cognitive framing with the detection of strong causalities will guide entrepreneurs to organise the production into an increasingly near-decomposable system. While it is relatively easy to develop cognitive frames and structure the firm accordingly, the relations between activities, workers and artefacts are more opaque because they are to some extent tacit. As long as an activity is not broken down into primitives of movements and actions, causality is not perfectly detectable. The recursive application of the subdivision of tasks goes a long way in this direction. It permits the framing of single actions into known categories and detecting co-variation between them. This leads to a better understanding of the relationship between different skills, routines and heuristics.

Problem decomposition is the "divide" part of the "divide and rule" heuristic. In this process tacitness is reduced and potential appropriability increases due to the increase in codification. But "divide" alone helps only to shed light on the sources generating non-separabilities. It is a necessary but not sufficient condition for "rule". "Rule" is only possible if new knowledge is created *and* appropriated and used to maximize the objective function of the firm. As it is the owner of the means of production who has the right to appropriate the outcomes of economic activity in this process, this is where a transition of intellectual property from the worker to the firm takes place.

2.2.2 Recombining codified and tacit knowledge to increase control: modularity and new knowledge

The process of problem decomposition generates information about the constituting elements of a problem and causal linkages between them. It is now possible to generate new procedures and routines to improve the performance of a firm. These new routines will reflect a solution to violations of the objective function. We move now into the "impera" domain of the "divide and rule" heuristic. The generation of new routines results from the recombination of sub-activities mostly within, but also between subsystems. Past experiences with problems similar to the one that has triggered search will act as an important starting point for any effort. They provide cognitive frames, which allow for the building of analogies and understanding the problem. This is a process that cognitive psychologists have called "slippage" (Holyoak and Thagard, 1992). The model of a well-understood situation is applied to a new problem and deviations are analysed. The case study in this paper shows, that the experience American engineers had gained in redesigning products to use standardised and interchangeable parts was important prior procedural knowledge in the efforts to reorganise the administration.

Wagner and Altenberg (1996) suggest two mechanisms for the differential suppression and re-grouping of linkages in existing routines. The first is called *parcellation* and it consists of the suppression of interconnections of lower importance between activities influencing the same group of characteristics of the product technology. The second is *integration* where linkages are selectively established between previously unrelated parts - new and old - of the process technology. Both favour the development of a more modular design of the process technology, as shown in figure 3. Frenken (2002) applies this to the evolution of modularity in organisation, where by modularity we mean an organisation of work in which the complementarities and linkages of two activities I_1 and I_2 fall mainly among sub-processes within one activity and are less frequent between them (see Wagner and Altenberg, 1996). This definition clearly overlaps with that of a near-decomposable system and stands in partial contrast to the definition of modularity used by Langlois (2002), as he views modularity as (perfect) decomposability assuming the redundancy of functionalities.

[Figure 2 about here]

The economic effects of increased modularity in production are threefold. First, adaptability is increased if the linkages between the related parts of the process technology are organised into standardised interfaces. It is easier to change sub-elements if their relation is standardised. This allows for increased redundancy (and competition) between sub-elements carrying out standardised activities linked through each other in standardised channels. This is an important characteristic of modularity.

Second, simulation results support this view as they show that in modular technology characteristic maps the likelihood of successful improvements increases, as they are less likely to be offset by negative feedbacks. Frenken, Marengo and Valente (1999) have shown that problem decomposition and the modularisation of a problem over a complex system dominates other search strategies in terms of the speed of convergence to higher levels of fitness. This underscores the claim that modularity is an important competitive advantage, as it increases the long run probability of survival (for a discussion see Simon, 2002).

Aside from achieving faster convergence to higher levels of fitness, modularity also achieves another important feature: modularity permits increased control over activities causing imbalances. The reason is straightforward: A higher degree of modularity increases the separability in production. The regrouping of links between basic work modules or primitives of an activity detracts it from the control of the original owner of its tacit elements. This process of extraction works in different ways along the lines of parcellation and integration: (1) some basic work primitives and their relations may be used to generate technological blueprints which will be embodied into new machines, (2) they may become part of the organisation capital of a firm through embodiment into the work-flow design of the organisation, and (3) knowledge about linkages and work primitives may be collected and grouped into activities coordinating the interaction between basic work modules and thus act as an interface between them. Parcellation and integration thus lead to the formation of new activities new machines and labour, the formation of coordinating activities and a specific work flow design. As the creation of new knowledge always also implies the generation of some new tacit knowledge, it is likely that new tacit knowledge on how to operate new machines and how to coordinate new activities will generated. It is not possible to predict whether the tacit knowledge extracted will exceed the tacit knowledge created on the basis of the present analytical framework. One cannot assert that the tacitness of the whole process has decreased. However, the control and appropriability of knowledge in the decomposed activities will have increased.

Figure 1c illustrates the arguments advanced in the previous paragraphs. The matrix in part b) shows a system with three activities producing output characteristics C_1 to C_3. Activities $I_{1'}$, I_2 and I_3 are all highly interrelated with each other. $I_{1'}$ is a central activity, as it influences all characteristics C_i. A change in any of the sub-activities of I_1 will affect I_2 and I_3 through feedbacks. Matrix c) shows a perfectly modular production architecture in which activity I_1 in matrix b) is decomposed into activities $I_{1'(1)}$-$I_{1'(3)}$, which are not linked to each other. Activities I_2 and I_3 now have a higher order aggregating and relating them. Improvements in any of the activities $I_{1'(1)}$-$I_{1'(3)}$ do not influence other parts of the system besides the interface, and the interfaces mediate only between two activities. Once this design of the process technology is achieved, the system can be gradually improved without risking losing control over the output characteristics C_i and thus of the performance of the firm. This process comes to halt when the increases in profitability through recombination vanish. Control over activities I_2 and I_3 gives control over and coordinates the single elements of the original activity I_1. Information on the linkages of the single elements in I_1 has passed over to activities I_2 and I_3, which may be either machines carrying this knowledge or coordination activities and organisational routines, which are now part of the organisation. Control has been detracted from the original activity $I_{1'}$ and passed on to the coordination activities, which have now gained relative importance in relation to the activities $I_{1'(1)}$-$I_{1'(3)}$, which now can no longer operate without the action of I_2 and I_3. In the process of creation of these new activities (i.e. work routines and machines) new tacit knowledge is also generated, but those people whose activities have been decomposed do not necessarily any longer have the right to dispose over it in the production process. If this knowledge has been embodied in the organisation or a machine, it passes over to whoever exerts the property rights over these entities. If it instead passes over to (possibly different) individuals, it increases their relative power within the organisation.

2.3 Appropriability and appropriation

The exploration and exploitation of a technological paradigm is constrained in several ways. Property rights are constraints, as they provide the definition of the objective function of the firm and related measures of performance. The latter acts as an information filter to indicate deviations from targeted performance values. In case it indicates a loss of control, action is taken. This eventually determines the direction of technological search. Problem decomposition and recombination is calibrated against the objective function. In this way, property rights constrain and codetermine the process of problem decomposition and searching on the technological landscape.

There are several implications resulting from the discussion of the process of problem decomposition, co-variation detection and recombination: First, with the degree of codification of the knowledge involved in economic and technological activities the degree of its appropriability increases (see Saviotti, 1998) along with control over the activities. Second, the break-down of productive knowledge in elementary tasks, along with their recombination, increases the specialisation of activities and augments the possibility to develop specialised machinery because the knowledge acquires blue-print character. We should thus observe an increase in the degree of mechanisation of work. Third, it is likely that the organisation of production becomes more modular, as the increasing division of labour is accompanied by a re-grouping of activities, which makes the organisation of a firm more modular and less integrated.

Modularity implies that a hierarchical structure emerges, which connects specialised units of production and decentralises authority over the execution of tasks. These units are related to each other through relatively stable and standardised channels of communication, and together these structures embody organisational knowledge. They can be aggregated into organisational units of higher order, which may lie inside or outside the firm. The choice of either of these options will depend on its effect on the objective function imposed on the firm by its owners. In the case of integration authority is re-centralised and the complex system can be grasped in its entirety. In the case of out-sourcing, the market mechanism takes over the task of co-ordination. In each case, the relative weight of activities of coordination increases at the cost of activities of production, from which knowledge is extracted.

3 The search for modularity in the transformation of office work, 1880-1930

By following the path of the labour process literature we use the rise of the white-collar working class as a case on which to apply our framework. The advantage of this case is that administrative work is a highly interrelated activity. We offer an interpretation of this process in accordance with the framework put forward in the preceding section.

3.1 The development of a new information system: the accounting revolution from the 1870s to the1890s

The process of developing an efficient cost accounting information system took place in two overlapping stages. In the first the inside contracting system was broken up and modern large business hierarchies emerged. The second stage saw the transformation of the information processing activities themselves as a response to constraints that were generated by the new information processing system.

The typical office in the 19th century up to the late 1870s was virtually untouched by technology and consisted of predominantly male workers. Clerical work had the characteristics of a craft as the skills were acquired by on-the-job training. (Cooper and Taylor, 2000; Braverman, 1974). Accounting records primarily reflected external market transactions. In larger firms forms of inside contracting were the prevalent method of control. The contracting of internal craftsmen avoided administrative overheads and acted partly "as a substitute for accounting" (Hopper and Armstrong, 1991, p. 415). The manufacturers set their prices on the base of their cost information but were not able to intervene directly on their determination, as they could not co-ordinate the production process.

The introduction of new production technologies and the increase of the size of the firms created the need for new methods of management. The reaction to this need was the Systemic Management movement that gained large support in US manufacturing in the late 1870s (Litterer, 1963). It "based its reassertion of control and co-ordination on record keeping and flows of written information up, down, and across the hierarchy" with the aim to "transcend reliance on the individual in favour of dependence on system" and to monitor and evaluate performance (Yates, 1989, p. 10-11). Systemic Management represented a set of procedures for decomposing activities into elementary work units.[4] A first step to take control of the activities on the shop floor was the direct payment of wages and salaries. This led to the demise of the inside contracting system, and salaried foremen replaced contractors. The property rights of the owners were thereby reasserted and the power of the contractors broken.

The introduction of standard measures of performance for activities and sub-processes led to processes of parcellation and integration. Larger production units were broken up into smaller ones. Many of the decision tasks taken away from foremen were integrated into new centralised staff departments, which acted as an interface activity between the shop floor and the management of the firm. This reduced the scope of the foremen's authority greatly. Management gained direct control (through integration) over the activities on the shop floor as output requirements were standardised, precise production schedules introduced and performance monitored through detailed cost figures. Accounting and its transformation into a current cost management technique were instrumental in this process.

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[4] Scientific Management that was introduced with moderate success towards the end of the 1890s brought these principles to its limits (Boorstin, 1973, p. 369).

The formal bureaucratic structure was a result of a process of decomposition and re-composition. But as the information system was set up new constraints became binding for the information processing activities themselves, as summarised by the following quote from Beninger:

> *A crisis of control in office technology and bureaucracy in the 1880s, as the growing scope, complexity and speed of information processing [...] began to strain the manual handling system of large business enterprises. This crisis had begun to ease by the 1890s, owing to innovations not only in the processor itself (the bureaucratic structure) but also in its information creation or gathering (inputs), in its recording or storage (memory), in its formal rules and procedures (programming), and in its processing and communication (both internal and as outputs to its environment) (Beniger, 1986, p. 390).*

The large business administrations produced and processed information on a large scale. The need for qualified clerks and the low potentials for productivity advances made the constraints set by the labour market for clerical workers binding in the 1880s. In the three decades from 1880 to 1910 the share of clerical workers in the total working population increased from 1,1% to 5,1%: the number of clerks in the United States rose from 186.000 to 1.8 million.[5] These changes in number went hand in hand with the transformation of clerical work and the reorganisation of the office.

3.2 Finalising the information system: the mechanisation of the administration from the late 1880s to 1930s

The sheer size of the information processing volume and the labour intense character of the clerical activity inflated the bureaucratic structure. On a smaller scale, these circumstances resembled the situation that had led to the development of the American System of Manufactures four decades before (see Hounshell, 1984). Sources suggest that engineers played an important role in restructuring the bureaucratic machinery (McPherson, 1992). Their primary objective was to reduce the dependence of administrative processes on skilled clerical labour by making labour and capital good inputs separable. Their training in the tradition of American engineering provided the background for approaching this problem. The American System of Manufactures may be viewed as a meta-heuristic or problem solving algorithm for problems in the production sphere, which they applied to the organisation. The model was the system of modular production based on standardised parts and activities. The division of labour in administrative work thereby increased through the standardisation of tasks, data and information channels. In parallel, those activities for which this was possible were mechanised. The standardisation of data and tasks was an important precondition for the introduction of office machines, as they could unfold their full productivity potential only if a smooth flow of standardised and indexed information was available.

The role of parcellation and integration in this process becomes clear for the development of bookkeeping practices. Bookkeeping was sliced into a sequence of distinct and specialised occupations. A first step was to separate data handling, amenable to standardisation, from data analysis, which was not. Through this, the dichotomy of bookkeeping and accounting emerged. Bookkeeping activities were divided into activities of work preparation and activities of data manipulation. Work preparation tasks, such as the sorting of vouchers and receipts and the examination of related ledgers, were executed without mechanical aides, but reached a high degree of specialisation in manpower. In most cases one clerk was responsible for some subset of tasks with respect to one narrow subclass of accounts. Adding machines, calculators, bookkeeping and billing machines or even Hollerith systems were adopted. The organisation of

[5] Compiled form J.M. Hooks Woman's Occupations through seven decades US Department of labour 1947 and Historical Statistics, Abstracts of the US Series D57-71 Later: US Bureau of Census (1972). For details see Hölzl and Reinstaller (2000, p 8).

the accounting activities was turned into a modular system, as changes in one sub-activity were made independently from changes in other sub-activities. The increased division of labour re-classified clerical work into standardised and quasi-standardised activities.

The re-organisation of administrative work and the invention and development of supporting mechanical devices was a co-evolutionary process. Most information processing devices were invented and introduced on the market in the years between 1870 and 1890 (1873: typewriters, 1879: cash registers, 1885: calculators, 1889: Hollerith system, etc.). The key requirements of the new office machinery were summarised by Leffingwell and Robinson (1950, p. 282-3): To save labour, to save time, to promote accuracy and to relieve monotony.[6] One could add "in order to achieve an order of magnitude jump in office work productivity". The critical skills needed to perform quantitative or repetitive operations such as sorting or adding were embodied in some mechanism, and the machines could be operated without much previous training. For more knowledge intensive activities, such as typing and short hand taking in many cases an embodiment was not possible. Office machines were instead used to support the specialisation of labour. A strong complementarity between the new technological artefact and the operator was the result, but the standardisation of the user-interface, like the typewriter keyboard, also forced the standardisation of skills, and the separability of the process from tacit knowledge or skills specific to a single worker.

Typewriters were the first technology of the new office work regime. Their domains of application were all activities involving the distribution of information on small scale. The typewriter as a technical artefact was an innovation but did not in itself represent a productivity increasing technical advance. Its mechanical construction did not embody any specific clerical knowledge or skill so that its use did not automatically lead to a productivity increase. The standardised human-machine interface was the crucial criterion for its adoption. The (quite special) interaction of service requirements and technological characteristics that gave birth to the QWERTY keyboard is well known (David, 1985). The subsequent development of touch-typing played a crucial role in making the typewriter a viable technology for business administrations, as it contributed to producing a homogeneous labour supply. The co-existence of different keyboards with different practices would have lead to a segmentation of the labour market with an inevitably lower elasticity of supply. As typewriters were fixed capital firms organised their operations in such a way as to increase the rate of utilisation. This led to centralised services for typing, and to functional office departments, which pooled typing activities (Leffingwell and Robinson, 1950, p. 34). Typing became a profession and an administrative process in its own right. The typist had a clearly defined activity profile, which consisted of taking (shorthand-) notes and writing them on paper with the machine using a particular typing method. Standards of practice were attained by the standardisation of letter styles and forms, thereby influencing the way business correspondence was done (Leffingwell and Robinson, 1950, p. 143 ff.). Typing pools were formed through the integration of new activities into the administration.

As the large administrative organisations owed their very existence to the need to gather and evaluate quantitative data, the capability to perform simple mathematical operations was of foremost importance. Adding and calculating machines were general-purpose tools applicable to a vast range of uses. They embodied the most important skills of a good bookkeeper: quick and reliable computing. The locus of the labour saving potential was primarily the mechanical arithmetic unit and was independent of the skills of the machine operator. Operators could learn quite quickly to handle them, but did not need to know much mathematics. They did not even need how to know a specific standardised method of use such as touch-typing (see table 1). Bookkeeping machines evolved out of other office appliances and entered the market only in the 1920s. In most cases they were tailored to specific uses and were essentially made by combining adding machines with typewriters or normal adding machines with mechanisms allowing special carriage movements.

[6] These are the headings to sections on machine use in office work.

Hollerith machines or tabulating gear differed from the previous technologies. They were instrumental for the implementation of new organisational designs. This becomes clear if we consider that, to sell such devices, "a salesmen had not to sell the machine but the organisation" (Pirker, 1962, p. 79). Salesmen, who typically were trained engineers, acted as technical advisors as well as organisation designers. Organisational concepts developed for businesses in one particular sector were then used as blueprints for other firms in that sector. Tabulating gear was used to process company wide data on a large scale. Large business firms tabulating gear for sales statistics, payroll and inventory management, and later for consumer trend analyses.

A tabulating system consisted of punched cards (the media on which operating instructions and information were stored), cardpunch machines to transfer the information on the cards, sorting machines and a tabulator to count the sorted cards. This made them very flexible, as they could be re-programmed. The operation of tabulating machines was split into three distinct activities: (1) the codification of sorting and tabulating routines, (2) the codification of the information and (3) the evaluation itself, i.e. the actual sorting and tabulating of information. Accounting and organisation specialists carried out the codification of routines. Specific sorting and tabulating processes were stored on punched cards and could be used when necessary. The programming of routines and routine sequences was an activity that happened only sporadically at the set up of the machine and subsequent organisational changes. These programs made codified procedural knowledge on clerical operations readily available. Hollerith and Powers systems isolated productivity increases in data processing from the skills of the manpower almost completely.[7] The high specialisation and division of labour typical for the shop floor in the American System found its correspondence in a number of new occupations. Pirker (1962, p. 95) noted in regard to the organisation of work "for the first time something appears in the office, that can be compared to the working practice on the shop floor". Keypunch operators codified and controlled the information; sorters were responsible for the supervision of sorting and tabulating processes; lead-machine operators (also called tabulators) were responsible for the wiring of the control panels and the verification of the machines and programmers finally were responsible for programming and designing process flows. The skill requirements increased in ascending order: the skill requirements for key-punch operators and sorters was completion of primary school, tabulators needed to have specific technical skills and therefore mostly held secondary school degrees. The programmers were university graduates in mathematics or engineering, were seen as professional organisers and operated in a middle management environment (see table 1). In comparison to the other professions, only programmers were in short supply, but only a few were needed.

4 Discussion

Our case study provides some evidence for the theoretical arguments advanced in this paper. The change in the property rights regime, from an early capitalistic to the organised capitalistic form, triggered a reconfiguration of administrative processes in the US industry. The cognitive model guiding the generation of new routines and tasks was the organisation of the shop floor. The process of decomposition and regrouping of tasks through parcellation and integration led to a more modular design of the administrative hierarchy. New machines, which supported information processing, reduced the dependence on skilled clerical work. The number of activities in the realm of the business administration grew and became more specialised, reflecting the more modular organisational design. The outcome of this process can be summarised by the following observations on the design of the new activities and the related technologies:

[7] Exceptions were keypunches. Their efficient operation relied on the speed with which the codification could take place. In first place this led either to the adoption of the typewriter keyboard (for alphanumerical insertions) or a 10-key keyboard (for purely numerical insertions) with the keys ordered in four rows. Both allowed using touch-typing methods. As the codification of data continued to be the bottleneck in this technology, the use of standardised interfaces was important.

a) In the case where perfect codification was possible and the critical knowledge could be embodied in machinery, the skill requirements (or labour requirements) was reduced. An example is the calculator, where the critical productivity-enhancing factor , i.e. calculating, was embodied in capital.
b) When codification was only partially possible this led to a partial deskilling. Bookkeeping machines made it possible to separate the manual bookkeeping activities from more conceptual accounting process. Routine activity was standardised and facilitated by bookkeeping machines. The correct handling sequence of bills and their booking were embodied in the organisation of the labour flow. Finally, activities of evaluation of accounts and coordination were concentrated into the hands of few highly qualified accountants. The control over the activity of accounting was concentrated there.
c) When codification was not possible, capital goods appeared that supported the standardisation of the work process. The typewriter provides an example for this. The standardisation of the work process was realised by the standardisation of the interface between man and machine, lead to the emergence of standardised skills in typing. Control over the activity „writing" was increased by both the possibility of monitoring the performance of workers, and the standardisation of skills, which permitted increasing the supply of labour by fostering typing education.

However, decomposition and mechanisation are only one part of the story. The integration of processes into new business processes (organisational capital) is best illustrated by the example of tabulating gear. The introduction of tabulating gear embodying the bookkeeping activity led to the set up of new activities in an organisational set-up that fed the machines. The new knowledge was largely embodied in organisation programmers and software engineers. A new class of accountants, which coordinated activities on the basis of the results of the bookkeeping process, emerged. The history of tabulating gear shows that new processes were integrated in the new organisational machinery, and how office work was transformed by new tasks, activities, routines and interface activities. The case study presents the division of labour as a process of codification of knowledge, embodiment of knowledge in machinery and generation of new activities, routines and knowledge. The case shows clearly that in this process the control and power distribution in the governance of the enterprise changed towards the management and owners of capital.

Our study also supports the view that codification and knowledge creation, and the organisational set-up of a firm, are not neutral with respect to property rights. Property rights shape the identification of complementarity constraints and the adoption of solutions, as property rights in physical capital are well protected while expropriation of human capital is hard to protect. In the last one hundred years we have seen that critical knowledge was replaced by more and more sophisticated physical capital, standardised procedures and tasks. Some commentators (e.g. Zingales, 2000) claim that the strategy of replacing human capital with physical capital becomes less and less important. Our study suggests that this is only the case when tacit knowledge is too complex to be codified.

It is frequently contended that today human capital is the crucial asset for a firm's success. The question if this is indeed the case depends on whether a tacit crucial asset can be extracted from its holder. Rajan and Zingales (2000) present the case of the advertising agency Saatchi and Saatchi as an illustration of the claim that personal human capital is the most important asset in the enterprise of the knowledge economy: When shareholders, led by U.S. fund mangers, voted down a generous option package of Maurice Saatchi because they wanted to punish managerial self-interest, this led to the departure of Maurice Saatchi, followed by the resignation of several key executives. Together they formed the new advertising agency M and C Saatchi that in a short period of time captured some of the key customers of the original firm, which was severely damaged. This underscores a key argument of this study: the critical assets of an advertising agency are typically the personal contacts key employees have developed with customers. These are assets that are not codifiable. It would be straightforward to conclude from this that in an increasingly knowledge intense and service-oriented economy the relative power in a firm will shift from the owners to key-employees. But in light of our study, this view is likely to be misleading. An example contradicting this perspective is the recent attempt to introduce business-to-business contracting through the Internet. The creation of specialised marketplaces for intermediate products leads to a reduction of the personal (human) content in customer relations. This weakens the relative position of the sales force, whose tacit skills are replaced by standardised relations and "intelligent" sales databases on the computerised market place. Another example is case-tools used for computer programming purposes. Case tools support structured programming. For this purpose they also include automatic documentation generation mechanism and interface management tools supporting the interaction between different sub-modules of the code, which are handled by different individuals or groups of programmers. Case tools rationalise programming and increase the programmers' productivity, but they also weaken the power of programmers, as the standardised documentation procedures weaken their tacit knowledge on the code they have produced and support a more modular development design. In this sense, programmers are easier to replace when case tools are used.

The cases of business to business contracting and case tools show that the mechanisms analysed and described in this paper are also at work in knowledge-intensive environments. The more important the critical assets which cannot be codified and embodied into capital goods or organisational routines, as in the Saatchi case, the more power is located in the individual agents who hold this knowledge. However, if codification is possible, tools supporting centralised control and modularisation will be introduced. Thus, there is a dialectic tension between the creation of new knowledge and codification, as contended by Nonaka (1994) driven by asymmetry between non-codifiable personal knowledge and centralised control.

5 Conclusion

In this paper we have advanced an analysis of the division of labour by means of a complex systems approach. The complex systems perspective allows us to draw conclusions on the design of organisations and of technologies supporting the modularisation of activities. We assert that the Babbage principle consists of two distinct steps, the processes of problem decomposition and re-composition. The first has its roots in general cognitive principles applied to problem solving, and the latter is a manifestation of the property rights regime. Property rights play an important role as focussing device in the identification of inconsistencies in organisation and production in that they define the objective function of a firm. Deviations from the latter guide the direction of the innovation process. Identified problems in production are split up into sub-problems and after solving those the work process is re-composed giving rise to a more modular design of the organisation and technology of a firm. In this way the control of management over the production process increases. The new organisational forms and technologies adopted will support the codification of knowledge and its embodiment into capital goods or organisational processes.

Property rights and the limits to the codification of knowledge are identified as the most important forces shaping the process of organisational and technological change. We draw implications for corporate governance and the governance of the innovation process from our analysis and case study. The process of modularisation of the organisation of the firm removes knowledge and control from the lower layers of the hierarchy and concentrates it on higher levels. The governance of the innovation process is driven by the struggle for control over crucial assets, such as specific skills or knowledge. This is constrained by the codifiability of the underlying knowledge. If the knowledge is very complex and hence very costly to codify, the power balance between the capital and labour holding those crucial knowledge changes in favour of the latter. Some authors have argued that this is the case in the "knowledge-based economy". Our conclusion is that these studies have probably gone too far. They neglect that the loss of control over production violates the profit-making objective of a firm set out in the capitalistic property rights regime. This acts as a very powerful focusing device for innovative technological search.

	I_1	I_2	I_3
C_1	X	X	
C_2	X		X
C_3		X	X

a)

	$I_{1'}$	I_2	I_3
C_1	X	X	
C_2	X		X
C_3	X	X	X

b)

	$I_{1'(1)}$	$I_{1'(2)}$	$I_{1'(3)}$	I_2	I_3
C_1	X			X	
C_2		X			X
C_3			X	X	X

c)

Figure 1: a) The NK model (N=3 K=1) of figure 1 b) in a generalised representation. b) A generalised, non-modular NK model with activities I_2 and I_3 as core and $I_{1'}$ as general and highly interdependent activity. c) Decomposed version of b) with perfectly modular inputs ($I_{1'(1)}$-$I_{1'(3)}$) and co-ordination or interface inputs (core) (I_2-I_3). Adapted from Frenken (2002).

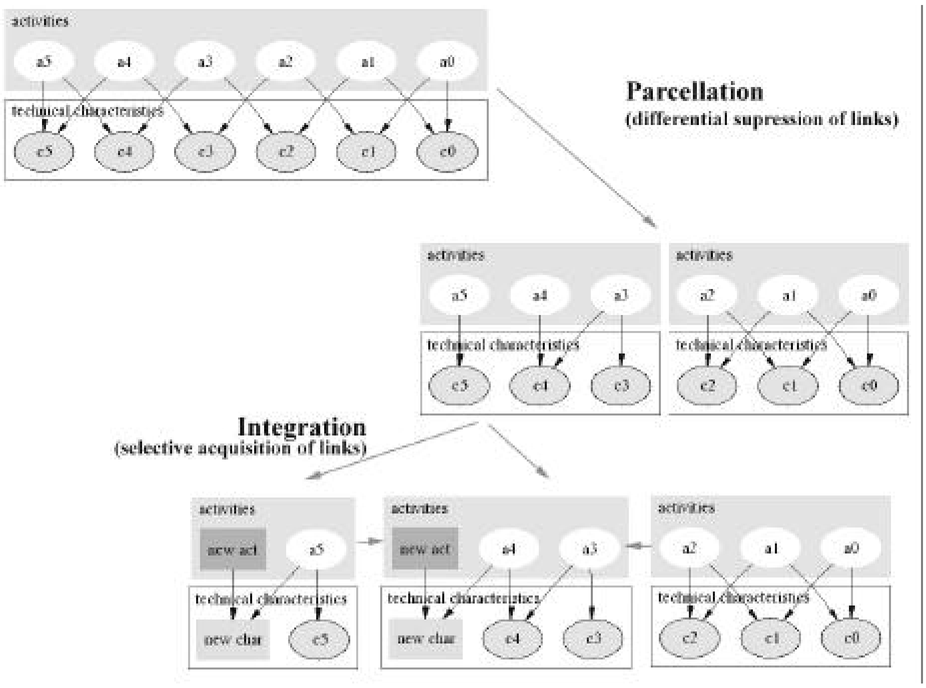

Figure 2: The effects of parcellation and integration in the redesign of the process technology. Adapted from Wagner and Altenberg (1996).

Table 1: Early information technology: innovation characteristics of the most important technologies of the IT Regime

Technology	**User side**			
	(i)Supported economic function of organisation and (ii) type of pro-cessed information	***(i) Source of productivity gains and (ii) effect on established competences, i.e. clerical work before IT Regime***	***New professions***	***Required skills***
Typewriter	(i) Co-ordination (ii) Multiplying codifying of qualitative information	(i) User interface, touch typing and complementary technologies (ii) Replacement of copyists	Typist; establishment of typing pools.	Touch-typing (about 60 words a minute), shorthand writing at least 60-75 words a minute (partly replaced by Dictaphones), good language and grammar skills, letter writing ability. High school degree preferred. Training period: approx.250-400 hours
Adding and calculating machines	(i) Monitoring (ii) Processing of quantitative (accounting) data	(i) Mechanical adding or calculating mechanism, automatic entry controls, user interface (ii) Replacement of mathematical skills;	In large enterprises Comptometer or adding machine operators; used in functionalised bookkeeping, sales or billing departments also on sporadic base. Establishment of computation pools.	Machine use. Touch-typing. Training period: few days. Girls of about 17 years of age with two years in secondary school.
Accounting machines	(i) Monitoring and allocation (ii) Processing of quantitative accounting data	(i) As for adding machines plus reduction of double entry mistakes through better work preparation (ii) Replacement of book-keepers (mathematical skills, book-keeping skills)	None; used in functionalised bookkeeping departments which took also the form of bookkeeping pools.	Machine use. Training period: accounting clerks with double-entry skills two weeks.
Hollerith – Powers systems	(i) Monitoring and allocation (ii) Processing of quantitative (accounting) data	(i) Electric contact principle, codification of information, sorting and tabulating mechnisms (ii) Replacement of mathematical and statistical skills; sorting and indexing tasks.	Card Puncher Sorter Tabulator Programmer; Establishment of card punch units, and machine rooms.	Puncher: in some cases typing skills mostly not; primary school degree. No further skills needed. Training period: 1-4 month Sorter: No special skills, but strong physical constitution required; primary school degree. Training period: about 6 month. Tabulator: secondary school degree and technical skills. Training period: 1,5 to 2 years. Programmer: organisational skills, business skills; preferably university degree in mathematics or a technical discipline. Training period: 4 years.

Source: Hölzl and Reinstaller (2000)

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