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THE ECONOMICS OF SYSTEM INTEGRATION: TOWARD AN EVOLUTIONARY INTERPRETATION

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1. Introduction

In this work we propose some elements of an interpretation of the dynamics of system integration (and disintegration) in the case of complex product systems (CoPS henceforth). The latter include a significant subset of capital goods such as most mobile communication systems, many military systems, corporate information technology networks, train engines, aircrafts, "intelligent buildings", air traffic control systems, tailored software packages, and many others.

CoPS differ from mass-produced goods in terms of product and production characteristics as well as patterns of innovation, competitive strategies, market characteristics and managerial constraints (for a thorough discussion, see Hobday (1998)). For example, design and implementation are usually carried out through major projects often involving also temporary multi-firm alliances. Moreover the multi-component and multi-technology nature of CoPS requires that manufactures be active in multiple technological fields in order to design, develop, integrate and manufacture products.

Research on CoPS has often emphasized the role of some key manufactures as coordinators of their own internal activities as well as the activities of a network of actors (such as component suppliers, but sometimes also universities, regulatory bodies, etc.) involved in the industry. Indeed, across many CoPS industries, a particular class of leading producers are responsible for the overall coordination of production and innovation: in the definition originally proposed by Rothwell (1992) they act as *system integrator*. In turn, such distinctive patterns of industrial organization hint at major interpretative questions with bearings well beyond the domain of CoPS themselves, and touching the very core of the analysis of economic organizations, their boundaries, their relationships with each other, their evolution.

In section 2, we briefly spell out a few of such questions which stand in the background and motivate our study. Section 3 presents an overview of evidence on the organization of design and production of CoPS, together with some elements of an interpretation. Finally, in section 4 we attempt to link the latter with an evolutionary theory of knowledge accumulation and organizations.

2. The changing Boundaries between Organizations and Markets: Some Background Issues

It would be futile to try to tackle here at any depth the determinants of those fuzzy and proximate boundaries separating what is done inside relatively coherent organizational entities whose inner working is only limitedly subject to market-type exchanges *vs.* what occurs through the intermediation of exchanges amongst independent actors. Here, suffice to recall some different, albeit *not* mutually exclusive, lines of interpretation.

A *first* one, dating back to (*parts of*) Adam Smith's *Inquiry* going all the way to Stigler (1951) and (1968) and to e.g. the refinements on 'complementarities' by Milgrom and Roberts (1990) focuses on the performances of particular tasks and on the advantages of specialization under certain indivisibilities and scale conditions. The famous pin making example of A. Smith is the archetype. Indeed, there is little doubt that "virtuous circles" between expanding scales of production, division of labour and increasing efficiency have been a powerful driver of secular productivity growth.

However, a distinct issue concerns the relationships between specialization across tasks *vs.* specialization across firms. Historically, the former is a robust stylized fact; much less so the latter. Firms are typically multi-task, and often multi-product, entities which *internally* govern the processes of division of labour and the coordination amongst separated tasks. What accounts then for such systematic discrepancies?

An answer is suggested, as well known, by a *second* line of interpretation of the boundaries of the firm, based on the nature of transactions and the related transaction costs - inspired by Coase (1937) and developed by Williamson (1975) and (1985). Here the unit of analysis are not "technical" tasks but elementary transactions: hierarchical organizations are compared to market forms of coordination in terms of relative efficiencies in transaction governance. The scope for opportunistic behaviours, depending in turn on asset specificities and other characteristics of transactions, twists the balance one way or another and - the theory suggests - shapes the approximate boundaries between organization-based *vs*. market based mechanisms of coordination.

Third, a different (but, to repeat, not necessarily alternative) interpretation focuses upon the *division of knowledge* - as distinct from the division of "operational" tasks - across organizations and upon organization-specific learning processes. It is a perspective which finds its roots in seminal works of Herbert Simon and collaborators (cf. Simon (1981) and (1991), March and Simon (1993))[1]. In a nutshell, such a perspective conjectures that proximate boundaries of corporate organizations are heavily shaped by the nature of the competences/capabilities organizations embody[2] and by their learning patterns. Organizational knowledge, in turn, applies to diverse domain such as a) allocative capabilities (e.g. deciding what to produce, how to price it, etc.); b) transactional capabilities (deciding whether to make or buy, etc.); c) administrative capabilities (concerning e.g. the designing of effective governance structures); d) problem-solving capabilities (concerning,

[1] Nelson and Winter (1982), Freeman (1982), Chandler ((1977) and (1990)), Richardson (1990), further developed in Winter (1987), Dosi and Marengo (1994), Patel and Pavitt (1997), Pavitt (1998), Teece (1996), Teece *et al.* (1994a) and (1994b), Dosi, Nelson and Winter (2000), amongst many others; and largely overlapping with "core competences" theories of the firm (Prahlad and Hamel (1990))
[2] For more detailed recent discussions of these notions cf. Dosi, Nelson and Winter (2000).

at large, the organization of design, planning, production, etc.); e) search capabilities (covering, in a shorthand, technological search for new products and processes of production, new organizational arrangements, new strategic positioning, etc.) (cf. Teece *et al.* (1994a)).

Note also the likely overlapping amongst the three foregoing perspectives.
For example, if organizational capabilities have mainly to do with the dynamic of transaction characteristics, the explanatory variables of the (changing) organizational boundaries mainly concern the features of the mechanisms for transaction governance (cf. the discussions in Langlois (1992) and Foss (1993)). Conversely, if one were able to neatly decompose "chunks" of knowledge and neatly map them into organizational activities, one would also get a large overlapping between "knowledge-centred" views of firm boundaries. Indeed, many analyses focussed on *technological modularity* hint at this interpretative perspective. In the management literature, modularity was first proposed as a product design strategy aimed at defining stable interfaces amongst components (modules) composing a product. Together, its is suggested, each module may be improved (e.g. via changes in design, the introduction of new materials, etc.) within a predefined range of variation, with little or no impact on the design of the other modules (Ulrich (1995)). The further step is the claim that modularity carries over from product design to the very characteristics of organizations. As, for example, Sanchez and Mahoney (1996) argue, if components' interfaces can be fully specified and standardized, they also determine *relatively stable product and production architectures.* Hence, also the processes for improving single modules may be de-coupled and carried out by independent organizational entities. Firms, therefore, may well choose to either specialize in the design (and/or assembly) of final products or in specific modules, largely leaving the interfaces to market exchanges.

Somewhat similar considerations apply to the role of market transaction concerning the very "chunks of knowledge" and, *in primis*, technological knowledge. Clearly, codification and (lack of) context-dependency influence the importance of market exchanges. In this respect, Arora *et al* (2001), Cowan *et al* (2000) suggest that, in fact, an increasing codification of technological knowledge fosters a growing importance of "market for technologies". The robustness and extent of this tendency is subject of lively debate (cf. Pavitt ( ) for another view).

In any case, we have here some major interpretative questions, including:

1. the relationships between division of labour (e.g. amongst operational tasks) and division of knowledge within and across corporate organizations;
2. the ensuing determinants of the proximate boundaries between activities internalized within single organizations and those mediated by market relations;
3. the very nature inter-organizational relations, hardly reduceable to impersonal exchanges.

With respect to all this issues, CoPS are a puzzling case to the point.

3. The messy dynamics of 'making' and 'knowing': some empirical evidence on the relevance of systems integration

There is growing empirical evidence that division of labour and division of knowledge, though connected, follow different and often apparently uncorrelated dynamics both within business organizations (Brusoni and Prencipe, 2001) and in the economy at large. In particular, the less-than-perfect overlap between knowledge and product boundaries of business firms has been corroborated by in-depth industry case studies based on both qualitative and quantitative evidence, as recalled below.

Based on systematic observations on US patent statistics in several industrial sectors, Granstrand *et al.* (1997) argue that decisions related to products are distinct from those concerning their underlying capabilities (e.g. technological). Thus, for example, outsourcing the production of components does not necessarily entail outsourcing the sets of knowledge employed to specify, design, integrate, manufacture, test and assemble them. They argued that "firms should maintain capabilities in exploratory and applied research in order to have the capability to monitor and integrate external knowledge and production inputs” (p.20).

Miller et al. (1995) in their study on the flight simulation industry underline the role of leading firms that act as integrators of other firms’ knowledge and activities. The knowledge bases of these systems integrators span many different knowledge domains and include:

- the scientific and technological fields underpinning the high variety of components and subsystems,
- organisational (e.g. project-management) and relational (e.g. marketing) capabilities required to manage and integrate the activities of multiple actors involved in the industry;
- knowledge about client requirements, and
- knowledge about rules and regulations for engine certification.

This in-depth study showed that the revolutionary changes (being technological or institutional in nature) that occurred in the industry heavily affected component suppliers but not so much flight simulator suppliers (i.e. the systems integrators).

Prencipe (2002) argues that in the aircraft engine industry although engine manufacturers make extensive use of collaborative agreements, they maintain a *broad* and *deep* range of in-house capabilities in order to understand and co-ordinate the technological workings of the network of suppliers involved in the industry. In particular, the aircraft engine industry is characterised by a set of driving forces whose combined effect ‘enables’ and ‘pushes’ engine makers to resort to suppliers to a greater extent than hitherto. The former forces include accumulated knowledge of the behaviour of the engine system, the knowledge codification process, increasing use of powerful computers, while major “pushing” factors include spiralling development costs, pressures from developing countries, and advantages of specialisation.

The modularization of the engine is just one (albeit an important one) of these driving forces. The impact of these forces has resulted in a greater division of labour between engine manufacturers and suppliers. In particular, due to accumulated knowledge of the behaviours about components as well as of the entire system, manufacturers are able to conceive engines in terms of modules and delegate the design and manufacture of larger engine parts to suppliers. As an industry expert summarised it “If I want to make a list of these 10,000 [engine] parts and I want to put a price against each of them, then the name of the supplier, you will find that between 60-80% of the total value is outside the systems integrator.”

However, despite increasing outsourcing of components, as the study by Prencipe showes, engine makers maintain a broad range of in-house technological capabilities and the *breadth* of these capabilities is shown to increase over time. While there is a trend in the industry towards a greater division of labour between engine manufacturers and suppliers, there is no evidence of increasing “technological focusing” and knowledge specialization of engine makers themselves.

The persistence of in-house multitechnology bases despite the increasing use of outsourcing policies points to the untidy trend followed by division of labour and division of knowledge. Indeed, if product decomposability does not necessarily entail knowledge decomposability, then the knowledge boundaries and the product boundaries of the firm are likely to differ. Decisions to outsource components do not necessarily entail outsourcing technological knowledge. Component outsourcing and technology outsourcing though connected are distinct phenomena. Prencipe (2002) argues that the scope for technology outsourcing for engine manufacturers is limited by two interrelated factors, namely (a) the technological and product requirements for the engine integration and (b) the need to co-ordinate the network of the actors involved in the industry.

Both factors foster the possession of profound knowledge in different technological fields. Engine manufacturers do divide up engine development tasks across a number of external suppliers, but this *task-partitioning* capability (Von Hippel, 1990) hinges on their multitechnology bases. Moreover, the capabilities of engine manufacturers must span over a wide spectrum of technologies in order to co-ordinate from a technological viewpoint the work of suppliers, airframers, airlines, and regulatory bodies, etc.. Co-ordination in this industry therefore, is not achieved through arms' length relationships but needs to be actively pursued by all-round knowledgeable engine manufacturers. Engine manufacturers act in other words as the *systems integrators* of the industry. Their multitechnology bases constitute their systems integration capabilities.

Brusoni (2001) finds similar evidence in his study on the chemical engineering industry. By comparing the evolution of the pattern of division of labour between operators and contractors, notwithstanding increasing product modularity, he highlights the persistent need for explicit efforts of co-ordination by so-called operators, which play the role of the systems integrators of the industry. In his words "despite the increasing involvement of contractors in high-level design decisions, all the operators involved in this study have retained in-house capabilities related to critical components. In particular, they maintain both conceptual and detailed design capabilities related to the reactor, which is the key component of the plant. Changes in this specific piece of equipment are likely to bring about systemic changes. Operators also maintain research units focused on the theory and modelling of reactor behaviour" (Brusoni, 2001).

Based on a longitudinal study of the Italian packaging machine industry, Lorenzoni and Lipparini (1999) identify within inter-firm networks the role lead firms that act as systems integrators of external specialised sources of components and knowledge for innovations. The packaging industry has been characterised by a continuous trend of outsourcing of tasks of different nature (design, manufacturing, and assembly) to first- and second-tier suppliers. As Lorenzoni and Lipparini (1999: 328) underlined, the boundaries of the leading firms of such network organisations have shrunk over time due to the "progressive disintegration of the manufacturing process".

The three case studies analysed by Lorenzoni and Lipparini, in fact, showed that all the lead firms under scrutiny increased their reliance on external suppliers. However, notwithstanding this increasing reliance on external resources, Lorenzoni and Lipparini found that "rather than using external ties as a substitute for capabilities which a firm has not yet developed, firms use collaborations to expand and improve their core competencies" (1999: 334). Again, these complementarities of organisational capabilities within a few firms rather than strict division of knowledge amongst firms themselves is consistent with the relevance of systems integration as a crucial co-ordination mechanism in network-like forms of industrial organization and the related importance of system integrating firms.

More specifically, with regards to CoPS industries, it is worth noting that the evidence has clearly shown that their products are characterised by two persistent trends, namely (a) incorporation of an increasing number of functionalities that increase the integration of the number of parts and components (multi-component) as well as services and (b) incorporation of an increasing number of new and sometimes distant scientific and technological disciplines (multi-technology). These two trends heavily impact on the definition of the boundaries of the firm (particularly make-or-buy decisions) since CoPS suppliers must increasingly resort to external sources of components, equipments, and technologies. Firms are required to set up and manage a network of institutions that are involved in the industry. As a consequence, systems integration capabilities are due to become even more important in the future.

The incorporation of services (e.g. maintenance, finance) and the move towards the supply of 'bundled' systems rather than individual subsystems (Tidd *et al*, 1997) is a trend that deserves separate treatment. Research on CoPS (Davies, 2002; Prencipe, 2002) has stressed that suppliers are moving downstream to provide bundled systems (integrated solutions or turnkey projects) to buyers. Bundled systems are comprised of hardware and software components often linked by proprietary interfaces that tie customers into a product and service solution with a single point of purchase and after-sales support. Suppliers of such solutions generate an increasing proportion of revenues through service-enhanced activities (e.g. maintenance and technical support) rather than manufacturing (Chandran *et al,* 1997).

In some industries, the move towards downstream business activities and the ensuing development of service capabilities by systems integrators has become a sort of “strategic imperative”. So for example the re-birth of IBM is ascribed to its reinvention as “solutions provider”. In the aircraft engine industry, shrinking margins, high development costs, and long payback periods to recoup the initial financial investment have prompted engine makers to explore new ways of pricing engines that would better stabilise their revenue stream. Leasing agreements, where manufacturers lease their engines rather than selling them, represents an option. Rolls-Royce in the 1970s had already introduced *power-by-the-hour* agreements for operators of corporate jets, according to which customer airlines pay a fixed rate that includes both capital and operating costs. This agreement provides an incentive to the manufacturer to improve engine reliability and reduce maintenance costs because it manages the entire engine life cycle: engine manufacturers provide an integrated system solution. Airlines might benefit too, since with improved engine reliability they have less down time.

In turn, in order to offer *power-by-the-hour* agreements engine manufacturers need a sufficiently large number of ground maintenance facilities spread around the world. This can be achieved either by acquisitions or via agreements with existing independent maintenance companies. Together, reliable engines and fast maintenance operations provide engine manufacturers with a competitive lead. Information related to engine behaviour becomes extremely valuable and a real time engine monitoring system is the tool to garner it. Digital engine control systems equipped with engine health diagnostics become necessary for engine manufacturers wanting to offer power-by-the-hour agreements (Prencipe, 2002). All in all, the process does not entail higher degrees of vertical integration when observed from the point of view of the actual production of goods and services, but does involve an extension of the knowledge bases which system integrators are required to master.

All the foregoing examples suggest patterns of: a) vertical disintegration in production, b) (complementary) “Smithian” specialization in particular components, and c) persistent concentration of broad knowledge bases within few “system integrators”.

Partial counterexamples to these patterns are equally revealing: consider for instance the case of telecommunications, where a tendency toward vertical disintegration in production still applies. However the importance of broad based knowledge carried by system integrators might actually be diminishing, this does not imply a diminishing importance of system integration activities, rather the latter appears to be pushed “upward” and embodied into the producers of crucial components. To a significant extent, system integration is increasingly incorporated into the underlying microelectronic components.

4. Empirical Patterns and Theoretical Interpretations

The foregoing evidence abundantly support the notion that explicit activities of system integration, in the presence of widespread component specialization, are a fundamental coordination mechanism which hardly falls within the scope of the rudimentary representations of market exchanges familiar to a good deal of economic theory. Such integration activities are performed by specific types of organizations - distinct in terms of technological and coordination capabilities. At the same time, the degrees of vertical integration of these firms vary also as a function of the nature and dynamics of multiple competences and subsystems technological trajectories.

How does one interpret this evidence? Teece et al (1994b) conjectured that the proximate boundaries of firms are shaped by the interplay between technological opportunities; convergence/divergence of technological trajectories; degrees of cumulativeness of idiosyncratic technological learning; and asset specificities.

The patterns displayed by CoPS broadly corroborate the general notion emphasized by Teece et al., but common to the evolutionary literature, according to which the nature and dynamics of technological knowledge is a fundamental determinant of the vertical and horizontal boundaries of firms. However, the evidence from CoPS also vividly illustrates a further distinction between different types of knowledge which organizations embody.

A first type relates, roughly speaking, to the “ability of doing things” and the way doing *A* affects or not the ability of doing *B* and/or the advantages and costs of governing market relations when selling and buying *A* or *B*. Clearly, this is also a domain where evolutionary, knowledge centred analyses significantly overlap with both transaction cost interpretations of make vs. buy behaviours and also “Smithian” interpretations based on specialization-driven increasing returns.

A second, somewhat distinct, type of knowledge regards “how products are put together”, that is how multiple components, possibly manufactured by independent producers, are ultimately assembled into complex products (cars, airplanes, steel plants, flight simulators, submarines, etc.) which generally perform the task they are meant to, notwithstanding the lack of either central planners or magic pre-existing modularity between components.

Finally, organizational knowledge concerns how to “search for what is not already there”, and possibly how to coordinate search efforts amongst independent agents. CoPS, we suggest, highlight dynamic patterns whereby knowledge accumulation in these three foregoing domains are only loosely coupled. An important observable consequence entails diverging dynamics in the scope of what firms do vs. what (some) firms know.

In this vein, Brusoni, Prencipe and Pavitt (2001) argue that distinct *system-integrating organizations* are a fundamental node in loosely coupled systems which emerge when complex products are characterised by either uneven (and relatively high) rates of change in the underlying technologies (even when component complementarities remain rather predictable), or, conversely, when interdependency patterns tend to change in unpredictable ways.

In these circumstances "system integration" entails technological and organizational capabilities to integrate multiple changes in components and subsystems only partly designed or even forecasted by "integrators" themselves. Together, "system integrators" are crucial in the persistent, imperfect, efforts to match the untidy dynamics of division of "operational" labour, knowledge accumulation and cross-corporate division of competences.

Granting all this, what kind of "reduced form", relatively abstract, formal representations can one offer of such organizational structure, if any? A basic building block regards the explicit account of organizations as repositories of *problem solving procedures.* In Marengo et al (2000) one develops a formalism aimed to capture diverse and (most often suboptimal) routines of production and search embodied in different firms.
Let us start by presenting the basic qualitative features of such modelling exercises (More in Hobday, Dosi, and Marengo (2002)).

In the view proposed here, the basic units of analysis for problem-solving behaviour (PSB henceforth) are, on the one hand, elementary physical acts (such as moving a drawing from one office to another) and elementary cognitive acts (such as a simple calculation) on the other. Problem-solving can then be defined as a combination of elementary acts within a procedure, leading eventually to a feasible outcome (e.g. an aircraft engine or a chemical compound). Or, seen the other way round, given the possibly infinite set of procedures leading to a given outcome or product, it is possible to decompose these procedures into diverse series of elementary cognitive and physical acts of varying lengths which may be executed according to various possible execution architectures (e.g. sequential, parallel or hierarchical).

PSB straightforwardly links with the notion of organisational competencies and capabilities. First, a firm displays the operational competencies associated with its actual problem-solving procedures (in line with the routines discussed by Nelson and Winter, 1982 and Cohen *et al.*, 1996). Second, the formal and informal organisational structure of the firm determines the way in which cognitive and physical acts are distributed and the decomposition rules which govern what is and what is not admissible within a particular firm (providing a route into the analysis of incentive structures and processes). Third, the organisation shapes the search heuristics for, as yet, unresolved problems, thereby governing creative processes within the firm.

This theoretical approach to PSB within the firm also closely corresponds to empirical accounts of firm behaviour from the economics of innovation (Freeman, 1982; Dosi, 1988;

Pavitt, 1999). Moreover, it has the benefit of being applicable both to the analysis of intra-firm structures and to the analysis of the boundaries between firms and the market. Indeed, such boundaries can be seen as particular patterns of decomposition of an overall problem-solving task. In other words, the boundary of the firm is shaped, in part, by the problem to be solved, often corresponding to the product to be created (e.g. a car or a piece of steel). Particular decomposition strategies may notionally range from the totally centralised and autarkic types (with no decomposition at all) to the equivalent of an ideal pure market, where one person acts on each task with market-like transactions linking each elementary act.

It is helpful to think of complex problem-solving activities as problems of design: the design of elaborate artefacts and the design of the processes and organisational structures required to produce them. In turn, these processes require the design of complex sequences of moves, rules, behaviours and search heuristics involving one or many different actors to solve problems, create new "representations" of problems themselves and ultimately to achieve the techno-economic goals at hand. Common to all these design activities is that they involve search in large combinatorial spaces of ‘components’ (as defined above in terms of elementary physical and cognitive acts) which have to be closely co-ordinated. To complicate matters still further, the functional relations among these elements are only partly understood and can only be locally explored through a process of trial-and-error learning, often involving also the application of expert, partly tacit knowledge.

For example, the design of a complex artefact such as an aircraft or a flight simulator requires the co-ordination of many different design elements, including engine type and power, wing size and shape and other materials. The interaction between each of the sub-systems and components is only partly understood and each comprises many smaller components and sub-systems (Miller et. al, 1995; Prencipe, 1997). The interactions between the elements of the system can only be partly expressed by general models and have to be tested through simulation, prototype building, and trial-and-error moves where learning and tacit knowledge play an important part. Producing an effective solution, such as a new aircraft, involves a long sequence of moves, each of which is chosen out of an enormous set of possibilities. In turn, the relations among the moves in the sequence can only be partly known as a full understanding would (impossibly) require the knowledge of the entire set of possibilities. The likelihood of combinatorial explosion within the search space presents a computationally intractable task for boundedly rational agents.

Business firms as well as collaborative ventures among them can be seen as complex, multi-dimensional bundles of routines, decision rules, procedures and incentive schemes, whose interplay is often largely unknown both to the managers of the organisation and also to managers, designers and engineers responsible for single projects. Of course, over time many repeated technical and business activities become routinised and codified, allowing for stable, formal structures and established codified routines as, for example, in the volume production activities of automobiles or commodity chemicals. In these circumstances, some sort of "steady state" problem decomposition becomes institutionalised, also allowing the establishment of neat organisational structures, and, together, the exploitation of economies of scale and scope. The "Fordist" and "Chandlerian" archetypes of organisation are the classic example. This is also the organisational arrangement which most forcefully highlights potential advantages (and also the in-built rigidities) of division of labour and specialisation. However, even in this stable case there remain many non–routine, complex activities within the firm, including new product design, research and development, new marketing programmes, etc. Even more so, under conditions of rapid market and technological change all organisations are ultimately forced to shape their structures in order to respond to new market demands and to exploit new technical opportunities (see, for example, the related discussions by Coriat and by Fujimoto in Dosi, Nelson and Winter (2000) on Japanese – “Toyotist” – organisational arrangements and routines).

During the multi-stage product design task, the basic elements to be co-ordinated are characterised by strong interdependencies which create many local optima within the search space. For instance, adding a more powerful engine could lead to a reduction in the performance of an aircraft or prevent it from flying altogether if the other sub-systems and components are not simultaneously adapted. Similarly, at the organisational level, the introduction of new routines, practices or incentive schemes which have proven superiority in another context, could also prove counter-productive if other elements of the organisation are not appropriately adapted to suit the new inputs (Dosi, Nelson and Winter, 2000).

A helpful although rough ‘reduced form’ metaphor of the complex task problem is presented in Kauffman’s (1993) model of selection dynamics in the biological domain with heterogeneous interdependent traits. Kauffman considers a model of the selection mechanisms whereby the units of selection are complex entities made of several non-linearly interacting components. Units of selection are combinations of N elementary components which can assume one of a finite number of states and a fitness value is exogenously assigned to each combination, producing a fitness landscape on the space of combinations whose characteristics reflect the interdependencies among the constituent elements. His model shows that as the number of interdependent elements increases the fitness landscape presents an exponentially increasing number of local optima. In the presence of strong interdependencies (as often the case in many complex products) the system cannot be optimised by separately optimising each element it is made of. Indeed, in the case of strong interdependencies it might well be the case that some, or even all, solutions obtained by tuning "in the right direction" each component yield a worse performance than the current one.

In the presence of strong interdependencies the problem cannot therefore be decomposed into separate sub-problems which could be optimised separately from the others (Marengo, 2000). As argued by Simon (1981), problem-solving by boundedly rational agents must necessarily proceed by decomposing a large, complex and intractable problem into smaller sub-problems which can be solved independently. Within the firm this is equivalent to a division of problem-solving activities. Clearly, the extent and efficacy of the division of such problem-solving efforts is limited by the existence of interdependencies. If, in the process of sub-problem decomposition, interdependent elements are separated then solving each sub-problem interdependently does not allow overall optimisation. As Simon (1981) pointed out, a perfect de-composition, which isolates in separate sub-problems all and only the elements which are interdependent to each other, can only be designed by someone who has perfect knowledge of the problem: boundedly rational agents will normally try at best to design ‘near-decompositions’. The latter are decompositions which try to isolate the most relevant interdependencies (in terms of performance) into separate sub-problems.

However, unlike the biological analogy above, the design space of a problem faced by an engineer or a firm is not given exogenously but, rather, is constructed by the agents as a subjective representation of the problem itself, in turn shaping a good deal of the search strategy. If the division of problem-solving labour is limited by interdependencies, the perceived structure of the latter, in turn, depends on how the problem is framed by the problem-solvers. Sometimes with major innovations, problem solvers are able to make major leaps forward by re-framing the problem itself in novel ways: for striking illustrations of the paramount importance of different combinatorics amongst already known system elements cf. on wireless communications Levinthal (1998) and on the Polaris missile system Sapolsky (1972).

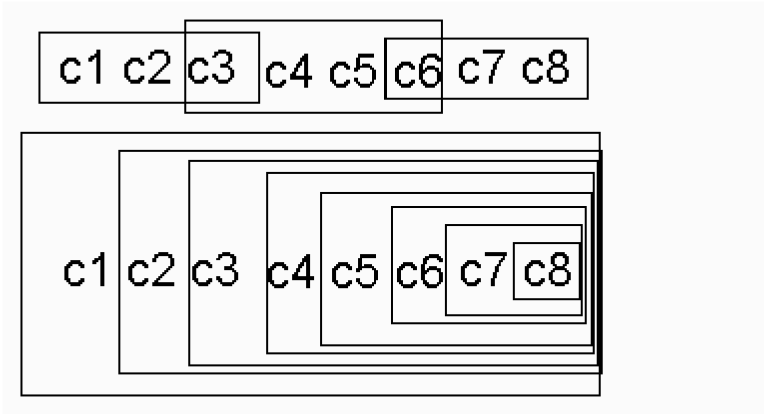
For the purpose of this work note, *first,* that specific decomposition schemes do not only mark the division of labour within individual firms but also the proximate boundaries between firms themselves. *Second*, in this framework one may straightforwardly represent the distinction between competencies on “how to do given things” vs. integrating and search capabilities. The former clearly include abilities in handling sub-problems, holding decompositions constant. Conversely, the latter refer to both the ways solutions to sub-problems are put together and to search patterns for new decompositions/recombinations of knowledge bases and physical components. *Third*, as conjectured in Simon (1981), near decomposable systems have an evolutionary advantage over systems which do not have this feature, because near decomposability increases the speed of adaptation, confines the consequences of errors and damaging events to sub-component of the system and guarantee the “evolvability” of the system, i.e. its capability to produce innovation without jeopardizing its overall viability and coherence. In particular there are two types of near decomposable architectures which are particularly relevant for our discussion, namely: a) an architecture of <u>partially overlapping</u> modules and b) an architecture of <u>nested</u> modules. In the former modules are separated but for some components they share. A system of nested modules is instead similar to Russian dollies in which there exists a small set of core components which belong to all modules then another larger set which includes the former and is contained in all the others and so on. Figure 1 depicts the architecture of both systems.

A system made of partially overlapping modules is in fact very close to Simon's idea of near decomposability and enjoys its properties of high adaptability and evolvability. With respect to search processes, in systems having this feature, components where modules overlap have obviously a special role since they are also the components for which search cannot be effectively decentralised. It is also easy to verify that those components which two subsystems have in common must be kept relatively stable because changes imposed by one subsystem will jeopardize the search process in the other subsystem. Some form of control over these interfaces among subsystems is therefore fundamental in order to keep the system coherent.

A system of nested modules has also specific characteristics investigated at greater length in Marengo et al. (2002): they are characterized by very strong interdependencies but nevertheless the search space remains highly decomposable provided that search proceeds sequentially from the "core" components, which have to be set first, to the more and more peripheral ones which can be adjusted sequentially.

Both partially overlapping and nested architectures have properties which are very similar to some of stylised facts about system integration presented in the previous session. Both architectures are based on the presence of some key components (and key agents) which are crucial for adaptation and evolvability and have to be kept relatively stable. At risk of overtheorizing, think of *system integrators as those agents holding knowledge about such major overlappings and interfaces.*

Figure 1: Systems with partially overlapping and nested components



5. Conclusions: some conjectures on the co-evolution of knowledge accumulation and organizational boundaries.

The long term history of many contemporary industries in general, and, closer to the concerns of this work, the dynamics of industries producing CoPS reveal puzzling divergences between what “firms do” and what “firms know”, or, putting it another way, systematic divergences between firms’ boundaries as revealed by the scope of production activities, compared to the scope of knowledge bases which some firms master.

The explanation of these patterns builds on evolutionary interpretations of the role of knowledge specificities in both production and innovation in different industries (cf. Freeman (1982), Pavitt (1984), Nelson et al (1999), Teece et al. (1994b), Piscitello(2000)). Ultimately, the punch line is that in many activities, firms need to “know more” than what is seemingly required by current production tasks. But such width of knowledge is often a necessary requirement for firms that perform as crucial knots in putting together complex outputs, and, even more so, whenever they want to continue to do that in the future. So, for example, General Motors reveals significant technological competencies in e.g. plastics, glass, etc., even if it does not produce them.

Indeed, robust evidence corroborates some long term tendency toward an increasing division of labour across firms, associated with an ever-lasting emergence of novel specialized industries (just think of the emergence of a distinct machine tool industry (Rosenberg (1963)), a pharmaceutical industry (Freeman (1982)), amongst many other examples). However, complementary to such long term trends, one has observed also, over at least a century, the emergence of large multi-technology multi-product corporations, characterized by varying degree of vertical integration, but always embodying rich integrative capabilities amongst multiple components and multiple technological bases.

Is something radically new happening today ?
A few analysts have emphasized a growing pattern of division of labour across firms corresponding to a spreading modularity between components which ultimately make up complex products (cfr. for example Langlois (2001), Pavitt (2002) and Sturgeon (2002)). Certainly, such process is at work in many industries. However, it is hardly a new phenomenon. At least since the 19th century, processes involving (i) "technological convergence" in operations common to a number of manufacturing processes; (ii) "output codification"; and (iii) the growth of markets large enough to sustain a number of small specialized firms (Pavitt (2002), p. 6) has frequently led to the birth of new specialized industries and to vertical disintegration. The evidence from CoPS is indeed broadly in line with such a pattern: specialization in production knowledge and task-specific increasing returns, among other factors, frequently drive also toward the separation of "chunks of tasks" between distinct firms.

Having acknowledged all that, however, a more controversial issue concerns whether "modularity" *cum* (some) codification of production knowledge will be sufficient to make the *Chandlerian Visible Hand* of multi-technology, often big, corporations vanish away (see Langlois (2001) precisely on the idea of a "vanishing hand"). Our conjecture, drawing on the evidence from CoPS, is somewhat different and suggests that, other things being equal, increasing "modularization" across components and specialization across firms goes hand-in-hand with *increasing requirements of integrative knowledge*. In turn, system integrators will continue to be crucial repositories of such knowledge. Clearly, the balances between what this type of firms "know" and what they directly "do" will continue to depend upon product- and technology-specific patterns of knowledge accumulation and their interfaces. Relatedly, while it is likely that such balances will move away from the profiles of heavy vertical integration displayed by classic "Chandlerian" firms, it is also equally unlikely that they will lead toward "hollow corporations" performing just the role of "brokers" or "middlemen" bringing together demand and supply of different components.

System complexity is there to stay(and possibly to grow) and so is the knowledge required to master interfaces and compatibilities across different components: this is indeed a first crucial task of system integrators. A second, equally important, task is often to bridge learning trajectories at component level. This is particularly important in all circumstances where system properties are not driven by innovation in any single crucial component (as indeed is to a good extent the case of microchips for computers, telecommunication, etc.). In these cases coordinating the diverse learning trajectories followed by independent component suppliers might indeed require the *expansion* of the knowledge bases which system integrators need to embody (although not necessarily the number of intermediate inputs they directly manufacture).

In the last resort, our conjecture, based primarily on CoPS but with much broader implications, is that the tendencies toward vertical disintegration and "Smithian" specialization (indeed a secular feature of modern economies) do not correspond to any general trend toward symmetric patterns of *division of knowledge* across firms. On the contrary, the more dispersed is production knowledge and the more complex products are the higher are also the requirement of explicit integrative capabilities embodied in what we have called system integrators. In many ways they represents the overlasting Visible Hand of purposeful organizations which painstakingly and imperfectly try to master, at each time, the exploding combinatorics among product components, and, dynamically, the coevolution among the diverse learning trajectories of "Smithian" suppliers.

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