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Modularity in technology and organization

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Abstract

This paper is an attempt to raid both the literature on modular design and the literature on property rights to create the outlines of a *modularity theory of the firm*. Such a theory will look at firms, and other organizations, in terms of the partitioning of rights—understood as protected spheres of authority—among cooperating parties. And it will assert that organizations reflect *nonmodular* structures, that is, structures in which decision rights, rights of alienation, and residual claims to income do not all reside in the same hands. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Modularity is a very general set of principles for managing complexity. By breaking up a complex system into discrete pieces—which can then communicate with one another only through standardized interfaces within a standardized architecture—one can eliminate what would otherwise be an unmanageable spaghetti tangle of systemic interconnections.

Such ideas are not new in the literature of technological design (Simon, 1962; Alexander, 1964), even if, as some claim (Baldwin and Clark, 1997), modularity is becoming more important today because of the increased complexity of modern technology. What *is* new is the application of the idea of modularity not only to technological design but also to organizational design. Sanchez and Mahoney (1996) go so far as to assert that modularity in the design of products leads to—or at least ought to lead to—modularity in the design of the organizations that produce such products.

From another angle, however, the principles of modularity have an even longer pedigree in the social sciences. We can think of Adam Smith's "obvious and simple system of

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natural liberty" Smith (1976) as among the earliest proposals for how a complex modern society might be made more productive through a modular design of social and economic institutions. In separating mine from thine, rights of private property modularize social interaction, which is then mediated through the interface of voluntary exchange, all under the governance of the systems architecture of common law. I will try to suggest that, despite its heavy emphasis on incentive issues, the economics of property rights that emerged from the work of Coase (1937, 1960)—in both its original form (Furubotn and Pejovich, 1972) and its more formal recent incarnation (Hart, 1989)—provides a good deal of material useful for understanding the nature and role of modularity in social institutions.

A Venn diagram would reveal only the thinnest of overlaps between the management literature on modularity and the economics of property rights. The management literature asks how and why firms should design modular products and how they should organize themselves internally to cope with those modular products. The literature on (what is implicitly) modularity in social institutions asks how the interactions among organizational units should be structured to increase wealth and promote economic growth. The overlapping question, of course, is Coase's question: what determines the boundaries of organizations? Why are some (modular) social units governed by the architecture of the organization and some governed by the larger architecture of the market?

This paper is an attempt to raid both the literature on modular design and the literature on property rights to create the outlines of a *modularity theory of the firm*. This theory will look at firms, and other organizations, in terms of the partitioning of rights—understood as protected spheres of authority—among cooperating parties. And it will assert that organizations reflect *nonmodular* structures, that is, structures in which decision rights, rights of alienation, and residual claims to income do not all reside in the same hands. The reasons behind alternative partitions are numerous and complex, however, calling for subtlety in the application of the idea of modularity to the firm.

2. Modularity and complexity

The world is full of complex systems. Nature provides an abundance of complex organisms and ecosystems, and humans have constructed complex mechanical, intellectual, organizational, and social systems. But what exactly does it mean for a system to be complex? For Herbert Simon, a complex system is "one made up of a large number of parts that interact in a nonsimple way. In such systems, the whole is more than the sum of the parts, at least in the important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole"[1] (Simon, 1962, p. 195). Complexity is thus a matter both of the sheer number of distinct parts the system comprises and of the nature of the interconnections or interdependencies among those parts.

One way to manage complexity, then, is to reduce the number of distinct elements in the system by grouping elements into—by hiding elements within—a smaller number of

[1] "Such 'wholes', defined in terms of certain general properties of their structure, will constitute distinctive objects of explanation for a theory, even though such a theory may be merely a particular way of fitting together statements about the relations between the individual elements" (Hayek, 1967, p. 26; see also *loc. cit.*, pp. 70-71).

subsystems. Simon argues for the criterion of *decomposability* in modular design, which he offers both as a prescription for human designers and as a description of the systems we find ready-made in nature. To make the latter point he offers the parable of the watchmakers. Tempus and Hora both make complicated watch-systems from myriad parts, and both are interrupted frequently in their work. Tempus does not design his watches as decomposable systems, so every time he is interrupted and forced to set aside his work, the entire unfinished assembly falls to pieces. By contrast, Hora first builds stable subassemblies that he can then put together in hierarchic fashion into larger stable subassemblies. Thus, when Hora is interrupted, only the last unfinished subassembly falls apart, preserving most of his earlier work. In an evolutionary selection environment, such stability would be rewarded with survival (Simon, 1962, pp. 200–205; Loasby, 1976).

In the end, however, what makes Tempus's unfinished watches so unstable is not the sheer number of distinct parts involved. Rather, it is the *interdependency* among the parts in his design that cause the watches to fall apart. In a nondecomposable system, the successful operation of any given part is likely to depend on the characteristics of many other parts throughout the system. So when such a system is missing parts (because it is not finished, for example, or because some of the parts are damaged), the whole ceases to function and the system becomes evolutionary shark bait. In a decomposable system, by contrast, the proper working of a given part will depend with high probability on the characteristics of other parts within its subassembly—but will depend with relatively lower probability on the characteristics of parts outside of that subassembly.[2] As a result, a decomposable system may be able to limp along even if some subsystems are damaged or incomplete.

In organizational and social systems—and perhaps even in mechanical ones as well—it is possible to think of interdependency and interaction among the parts as a matter of information transmission or *communication*. Consider, with Eric von Hippel (1990), the problem of organizing product innovation. Here, the issue is how to decompose the organization of a research and development project by partitioning tasks among development teams. As von Hippel points out, in order to solve this decomposition problem, one has to focus on the interdependencies among the various tasks the project comprises.[3] If the project is organized in a nondecomposable way, then interdependency will be high, meaning that each development team will need constantly to receive and use information about what all the other development teams are doing.

For example, the development of the OS/360 operating system for the original IBM 360 line of computers was evidently organized in a relatively nondecomposable way. The manager of the project, Frederick Brooks, insisted on a conscious attention to

[2] I won't elaborate the formalism, but this is clearly equivalent to saying that a decomposable system is one for which the matrix of interaction probabilities is decomposable. A nearly decomposable system—which is the best one could hope for in the real world—is the one in which the probabilities of interaction within the subassembly (submatrix) are much higher than those of interaction outside of it. Simon (1962 [1981, pp. 210-212] makes this point with an example using heat-transfer coefficients rather than probabilities. See also Alexander (1964, especially pp. 111 ff.).

[3] von Hippel defines "the interdependence between any two innovation project tasks with respect to problem-solving as the probability that efforts to perform one of the tasks to specification will require related problem-solving in the other. The higher this probability in a given instance, the greater the problem-solving interdependence" (von Hippel, 1990, p. 409).

interdependencies and a high level of communication among all participants. This included the creation and maintenance of a formal project workbook that documented every aspect of the system so that, in principle at least, every worker could determine how changes elsewhere would affect his or her part of the project. Brooks decided "that *each* programmer should see *all* the material, i.e. should have a copy of the workbook in his own office" (Brooks, 1975, p. 76). But within 6 months, there was one small problem. "The workbook was about 5 ft. thick! If we had stacked up the 100 copies serving programmers in our offices in Manhattan's Time-Life Building, they would have towered above the building itself. Furthermore, the daily change distributions averaged 2 in., some 150 pages to be interfiled in the whole. Maintenance of the workbook began to take a significant time from each workday" (Brooks, 1975, p. 77). The team soon switched to microfiche. And, clearly, with modern technology, the workbook could reside online and be updated rapidly. But the point remains that a nondecomposable system incurs high communications cost. Indeed, it is an insight for which Brooks is well known that, in the design of complex systems, the costs of communication among workers will eventually outweigh the benefits of the division of labor as more and more workers are added to a project (Brooks, 1975, pp. 18–19).

At one point, Brooks briefly considers a "radical" alternative proposed by D.L. Parnas, whose "thesis is that the programmer is most effective if shielded from, rather than exposed to the details of construction of system parts other than his own" (Brooks, 1975, p. 78). This radical alternative is in fact the strategy of seeking decomposability in the design of the development project and of the underlying software. Parnas (1972) is the inventor of the notion of *information hiding*, a key concept in the modern object-oriented approach to computer programming. Programmers had long understood the importance of modularity, that is, of breaking programs into manageable pieces. But a modular system is not automatically a decomposable one, since one can break the systems into modules whose internal workings remain highly interdependent with the internal workings of other modules. Parnas argued that, especially in large projects, programmers should abandon modularization based on simple flow charts and pay attention instead to minimizing interdependencies. If knowledge is hidden or *encapsulated* within a module, that knowledge cannot affect, and therefore, need not—*must not*—be communicated to other parts of a system. Under this scheme, every module "is characterized by its knowledge of a design decision which it hides from all others. Its interface or definition was chosen to reveal as little as possible about its inner workings" (Parnas, 1972, p. 1056).

Recently, Baldwin and Clark (1997, p. 86) have drawn on similar ideas from computer science to formulate some general principles of modular systems design. The decomposition of a system into modules, they argue, should involve the partitioning of information into *visible design rules* and *hidden design parameters*.[4] The visible design rules (or *visible information*) consist of three parts.

- An *architecture* specifies what modules will be part of the system and what their functions will be.

[4] As I have suggested, not all modular systems are decomposable. Baldwin and Clark—and most others—have in mind a decomposable or nearly decomposable modular systems. From this point on I will follow common usage and take modularity to imply if not decomposability, at least the goal of decomposability.

- *Interfaces* describe in detail how the modules will interact, including how they fit together and communicate.
- And *standards* test a module's conformity to design rules and measure the module's performance relative to other modules.

These visible pieces of information need to be widely shared and communicated. By contrast, the hidden design parameters are encapsulated within the modules, and they need not (indeed, should not) be communicated beyond the boundaries of the module.

As Baldwin and Clark point out, the literature on modular systems tends to collapse these three kinds of information together, calling them all either "the architecture," "the interfaces," or "the standards." In order to have a single term for all three, I will refer to a set of architecture, interfaces, and standards as a *modularization*.

3. Design processes

Clearly, modularity is a design structure with a great many advantages. By reducing the degree of interdependency among, and thus the costs of communicating across, the parts of a system, it gives full rein to the many benefits of the division of labor among components. As usual, however, there is no free lunch. It turns out that

> modular systems are much more difficult to design than comparable interconnected systems. The designers of modular systems must know a great deal about the inner workings of the overall product or process in order to develop the visible design rules necessary to make the modules function as a whole. They have to specify those rules in advance. And while designs at the modular level are proceeding independently, it may seem that all is going well; problems with incomplete or imperfect modularization tend to appear only when the modules come together and work poorly as an integrated whole (Baldwin and Clark, 1997, p. 86).

A well-decomposed modular system must pay a kind of fixed cost that an intertwined system need not pay, and this is true whether the system is brought to us by the evolutionary process or by a design team at Sony. Under some circumstances, the benefits of modularization may not be worth the cost. For example, a system whose environment never changes may not have to worry much about modularization: Tempus will do as well as Hora if neither is ever interrupted. Systems that develop slowly in a slowly changing environment may not acquire, or require, much modularity.

As we saw, a nondecomposable complex system that is consciously designed (as by a development team) requires a great deal of communication among the designers. In another sense, the system itself also displays a great deal of "communication" among the parts, in that the functioning of one part is highly dependent on the functioning of parts elsewhere in the system. But when a system is not consciously designed and instead develops slowly over time, learning can take place in a way that involves far less explicit transmission of information. As Alexander suggests in the context of architecture and urban design, many of the most attractive and durable systems are those (often traditional) ones that develop through an "unselfconscious" process. Whether the object is a building or a computer operating system, a designer must set forth design rules explicitly and communicate them clearly.

In the unselfconscious process, by contrast, “the rules are not made explicit, but are, as it were revealed through the correction of mistakes” (Alexander, 1964, p. 35). Inconsistencies and interdependencies are revealed not by ex ante communication but by trial-and-error.[5]

Alexander seems to think that traditional designs developed by the unselfconscious process will also tend to be modular. This certainly *can* be so: the modular design of the earliest PCs, which influenced the design of the IBM PC, was not the result of any conscious design (Langlois, 1992a). But it is by no means obvious that unselfconscious design must always, or even usually, result in modularity.[6] Under stable conditions, indeed, a nonmodular system may present certain advantages to an unselfconscious process of trial and error. As Brooks points out in criticizing the Parnasian approach to software, “a good information system both exposes interface errors and stimulates their correction” (Brooks, 1975, p. 78). To the extent that a nondecomposable system tends to reveal errors more quickly and more visibly, such a system may stimulate learning by doing in a way that modular systems do not. This is indeed the benefit of nondecomposability that Japanese manufacturing systems (including just-in-time inventory systems) are said to take advantage of it. Since the failure of any one part can cause total system breakdown, nondecomposability raises the cost of missing or poorly functioning parts, which in turn raises the incentive to make sure that each part is of high quality. Nondecomposability also highlights bottlenecks and inconsistencies.

One would expect, however, that the benefits of nondecomposability would dominate those of modularity only for some kinds of relatively stable systems where frequent change is not important. Although it did eventually have some modular aspects, Henry Ford’s production system for the Model T was on the whole a finely tuned and nondecomposable system for cranking out large volumes of an undifferentiated product. In the 1920s, this system could not adapt well to the changed market conditions and the (more modular) strategies of competitors, notably General Motors (Langlois and Robertson, 1989). History offers many other examples of nondecomposable systems that developed by trial-and-error in stable environments.

4. Encapsulation boundaries

In a world of change, modularity is generally worth the costs. The real issue is normally not whether to be modular but *how* to be modular. Which modularization, which structure of encapsulation boundaries, will yield the best system decomposition? The goal is clearly

[5] That complex systems can develop spontaneously through a process of trial and error should not come as a surprise to anyone who has studied Hayek or Karl Popper. On the latter’s “evolutionary epistemology,” see Radnitzky and Bartley (1987).

[6] In fact, one of Alexander’s own examples of an unselfconscious traditional system is clearly nondecomposable. Slovakian peasants once made beautiful colored shawls using traditional techniques. In the early 20th century, they replaced their traditional dyes with newly developed aniline ones—and “at once the glory of the shawls was spoiled; they were now no longer delicate and subtle, but crude” (Alexander, 1964, p. 53). When small changes in one part of a system lead to such dramatic changes in functionality, nondecomposability is at work. Indeed, scholars from here to Santa Fe have become enthralled with the possibility that complex systems may often display this kind of “chaotic” behavior. Notice, however, that, since modularity tends to limit the transmission of spurious effects within a system, the widespread incidence of modular design diminishes the importance of the phenomenon of chaos.

to find the modularization that minimizes interdependencies and most cleanly decomposes the system. But how to do this? How do we find the “natural” encapsulation boundaries? We would think it odd indeed to assign two interior designers each half of a room (von Hippel, 1990, p. 410). It makes a good deal more sense either to give each designer a whole room or to give up encapsulation entirely and let the two designers communicate extensively.

The problem of defining boundaries of encapsulation becomes even more challenging in a dynamic setting. For example, the tasks in an innovative development project cannot be partitioned in advance, since knowledge is continually changing.[7] In such a case, the modularization of the system (the development project) has to change continually; moreover, the modularization at any point has to take into account the inevitability of remodularization as learning takes place. In routine projects (like setting designers to work on a room), it may be possible to predict which tasks will become the sources of new information; but in genuinely novel projects, prediction becomes all but impossible.[8] Indeed, unpredictable novelty may make any hard encapsulation undesirable, calling instead for “loosely coupled” development teams of the sort evidently favored by Japanese companies[9] (Imai et al., 1985).

Of course, innovation need not always require or imply remodularization. In some cases, indeed, a fixed and predictable modularization can spur innovation. The personal computer is a case in point (Langlois and Robertson, 1992, pp. 301–302). With the advent of the IBM PC in the early 1980s, the microcomputer became a modular system with a relatively fixed (or at least slowly changing) architecture, interfaces, and standards. Despite—or, rather, because of—the slowly changing character of the PC’s basic structure, the industry experienced a phenomenal increase in value and reduction in cost arising almost entirely from improvements in modules (microprocessor, software, modems, peripherals, etc.) rather than from improvements in the way the modules connect together.

Innovation that takes place through change in the modules we can call *modular innovation* (Langlois and Robertson, 1992, pp. 301–302; Sanchez and Mahoney, 1996, pp. 68–69). This is in contrast to what Henderson and Clark (1990) call *architectural innovation*, in which the parts remain the same but the architecture connecting them changes. Notice, however, that architectural innovation need not always imply a change in the system’s visible design rules: Legos and Tinkertoys are classic modular systems designed for architectural innovation. Here the architecture—the way the unchanging parts are recombined—can change without a fundamental change in the overall modularization.[10] And, in fact, personal computers also benefit from the mix-and-match capabilities of a modular system that allow one to configure the system to taste as much as they do from improvement in the constituent modules (Langlois and Robertson, 1992).

Sometimes, however, improving the functioning of a system calls for remodularization rather than recombination. Since a remodularization will render the existing stock of

[7] This paragraph follows von Hippel (1990).

[8] Sanchez and Mahoney (1996, p. 71) suggest beginning the design process with well-understood technologies and then allowing periodic redefinitions of the modular product architecture as “loosely coupled” learning proceeds.

[9] In this context we can give a fairly precise meaning to this vague term: loosely coupled means modular but not fully decomposable.

[10] Clearly, the point of Legos and Tinkertoys is that the interfaces remain standard and unchanging. Whether “architecture” in the Baldwin and Clark sense (as opposed to the Henderson and Clark sense) also remains unchanged as the toys are assembled depends upon how finely one wants to parse the concept.

modules incompatible or irrelevant, systemic innovation comes at a cost. This indeed is one of the central insights of the much discussed literature on path dependency and technical standards.[11] Can systems get stuck in an inferior modularization because of the costs of remodularization? The answer will no doubt depend on the context.

A related issue arises in a dynamic setting. As we have seen, well-decomposed modularity requires visible design rules that are fixed and unambiguous. If the design rules are in flux, the possibilities for modular innovation and mix-and-match recombination will be limited. On the other hand, freezing the design rules too early may result in an inferior modularization. Whether Scylla is preferable to Charybdis will again likely depend on the particular circumstances. In some cases, the benefits of modular innovation and recombination are so great as to outweigh mistakes in modularization. Many have argued that the IBM PC was not the best available platform of its day, but its standardized modularity generated cost reductions and technical improvements at a rate that quickly left allegedly superior competitors in the dust (Langlois, 1992a).

Garud and Jain (1996) have suggested the ideal of what they call a *just-embedded* system, that is, a system in which the visible design rules are *enabling*—firm enough to encourage modular innovation and recombination—but loose enough not to be *constraining* to the evolution of the system. This may be easier said than done. But in the case of personal computers, the three main interface standards—those of the microprocessor, the system bus, and the operating system—have in fact evolved gradually in a way that supported modular innovation.

5. Modularity, property rights, and organization

One of the earliest, and still one of the best, general treatments of property rights in this literature is that of Armen Alchian, who defines a system of property rights as “a method of assigning to particular individuals the ‘authority’ to select, for specific goods, any use from a nonprohibited class of uses” (Alchian, 1965, p. 130). The notion of *authority* is useful, as it tracks well the principle that, in a well-decomposed design, hidden system parameters ought to be under the control of the module only and not of any other part of the larger system. Echoing a well-known maxim of liberal social thought, Alchian suggests drawing the boundaries so that each property owner has “the right to use goods (or transfer that right) in any way the owner wishes so long as the physical attributes or uses of all other people’s private property is unaffected.”[12]

[11] Buttressed by influential neoclassical models of network externalities (Katz and Shapiro, 1985; Farrell and Saloner, 1985), this intellectual edifice has as its keystone David’s (1985) famous history of the QWERTY keyboard. For critical perspectives, however, see Liebowitz and Margolis (1990, 1994); and for a general survey see David and Greenstein (1990).

[12] Notice that Alchian would limit the protection of property rights to infringements on the “physical attributes or uses” of one’s rights. This is in fact quite standard in liberal theories of property rights. It rules out as non-infringing harms that are transmitted through the price system, what economists call pecuniary externalities. I may not burn down your restaurant (an interference with physical attributes), but I may open a restaurant next door and seduce away your clientele. Since such pecuniary effects are moderated through the interface of the price system, they create no unaccounted for cross-module interdependencies. In addition, Alchian (and others) would rule out

The economic benefits of carving out a protected sphere of authority fall into two broad categories, the "concentration of rewards and costs *more* directly on each person responsible for them," and "comparative advantage effects of specialized applications of . . . knowledge in control"[13] (Alchian, 1965, p. 140, emphasis original). We might call these the *incentive* benefits and the *division-of-knowledge* benefits of property rights. Both are important, even if the first has attracted a disproportionate share of the attention of economists.[14]

Coase's famous 1960 article focused on the exchange of property rights: under which circumstances will a right end up in the hands of the party who values it the most? But the early literature springing from Coase's work also concerned itself with the creation and partitioning of rights. Economists have been well aware that the modular design of property rights comes at a cost, and that societies (and the economic agents within them) will want to pay that cost only if it is worth the benefit. Restaurant owners do not assert their full property rights over the salt they offer customers, but instead place the salt "in the public domain." Even though this destroys the patron's incentive to husband salt, any inefficiencies are dwarfed by the transaction costs of monitoring and charging for the use of the salt (Barzel, 1989, p. 66). Harold Demsetz (1967) took this idea as the basis for a theory of the emergence of property rights. New rights will emerge (or old rights will be altered), he argued, whenever exogenous conditions conspire to make the costs of modularization worthwhile. In Demsetz's example, the Montagnes of Québec had no need for a property rights system until trade with Europeans in the 17th century increased the demand for beaver pelts and created a tragedy of the commons. In the post-European era, the benefits of property rights outweighed the costs (monitoring mostly), so the Montagnes adopted property rights.[15] They did this in order to internalize externalities, that is, to eliminate the effect of other people's actions on each hunter's management of beaver.

This same process also lies behind the bundling and unbundling of rights. Indeed, the creation of "new" rights and the rebundling of existing rights are really manifestations of the same underlying process of modularization, remodularization, and sometimes even demodularization. In all these cases, the driving objective is to internalize externalities,

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intangible harms of a non-physical sort, what I once referred to as "transcendental" externalities (Langlois, 1982). I may not pour effluent on your property; but I may in seclusion read material you find offensive, even though your knowledge that I do so harms you (lowers your utility) just as surely as does the effluent. As Amartya Sen (1970) showed in a classic article, to define harms in terms of the effects of one's actions on the utility functions of others is to vitiate completely the liberal idea of a protected sphere of action.

[13] Alchian also mentions the comparative advantage effects of risk bearing, but I neglect this aspect of property rights here.

[14] A notable recent exception is Jensen and Meckling (1992, p. 251), who point out that economic organization must solve *two* different kinds of problems: "the rights assignment problem (determining who should exercise a decision right), and the control or agency problem (how to ensure that self-interested decision agents exercise their rights in a way that contributes to the organizational objective)." Efficiency demands that the appropriate knowledge find its way into the hands of those making decisions. There are basically two ways to ensure such a "collocation" of knowledge and decision-making: "One is by moving the knowledge to those with the decision rights; the other is by moving the decision rights to those with the knowledge" (p. 253).

[15] Douglass North (1990) and others would caution against a Panglossian interpretation of this theory, pointing out that entrenched interests and other sources of transaction costs can often prevent the adoption of new rights even when there would be considerable economic gains to doing so. Indeed, in historical and global perspective, the absence of potentially beneficial institutional change is the norm not the exception.

subject to the costs of setting up and maintaining the rights as well as to other considerations, notably the presence of economies of scale. Suppose, for example, that there are rampant externalities among a group of adjacent land owners. The owners could take account of these interactions by communicating among one another and negotiating contracts. This is clearly a nonmodular strategy: any new owner would face a web of restrictive covenants, and innovation that affected the nature of the externalities would require costly renegotiation. Alternatively, one of the owners could buy out the others, thus, placing all the interactions within a single module, where presumably they could be dealt with more cheaply—with less negotiation costs and, perhaps more importantly, with less adverse effect on the ability and incentive to innovate.

Dahlman's (1980) analysis of the medieval open-field system illustrates these points well. The open-field system dominated agricultural production (and therefore economic life) throughout Europe during the High Middle Ages. It was a complex system optimized for subsistence agriculture and near-autarkic production by manorial villages isolated from one another by high transport and transaction costs. The essence of the system was a fine partitioning and tailoring of rights to track the costs and benefits of the many different productive tasks on the manor. For some activities, like harvesting and the periodic grazing of cattle on fallow land, rights were held in common. This does not mean that the land was unowned like the beaver in Québec before the Europeans; rather, it means that actions were determined "collectively" by an elaborate set of management rules and practices evolved over time, overlain with a voting-based governance structure. For other activities, however, property was held privately, and the incomes of the peasants depended on the produce of particular parcels of land over which they held a residual claim.

Although each manorial village was a "module" in the medieval scheme of things, the open-field system was clearly not a decomposable system from the point of view of individual tenancy. Each peasant was an owner, but his rights were circumscribed by a thick web of restrictions and collective obligations. Since the system was adapted to a slowly changing environment, however, modularity would not have conferred much benefit. Moreover, the complex structure of the system was well optimized to its environment. For tasks with large economies of scale and low monitoring costs (like harvesting and grazing), management was collective. But for tasks involving low economies of scale and high monitoring costs (like cultivation and crop maintenance), high-powered ownership incentives prevailed.

As the Middle Ages wore on, intervillage transaction costs diminished and trade revived. This created gains from trade in specialization, which farming units could take advantage of only if they could reengineer themselves away from diversified subsistence agriculture. As North (1981) suggests, change proved nearly impossible despite the gains to be had; and it took a Malthusian crisis, including the death by plague of a third of Europe's population, to bring about a restructuring. The resulting enclosure movement involved in the main a voluntary unbundling of the complex relationships of the open-field system in favor of tenancy in fee simple, which not only allowed specialization, but also aided modular innovation in agricultural and business practices.[16]

[16] Morris Silver (1984) has stressed the role of enclosure in overcoming the costs of and restrictions on innovation in what had been a nonmodular agricultural system.

The open-field system is an example of what Michael Heller (1998) calls an *anticommons*. In a commons, like a beaver habitat without property boundaries, everyone has the unrestricted authority to use the resources in question. This results in the familiar tragedy of overuse. The anticommons, by contrast, is a situation in which no one has an unrestricted authority to use the resources; many people have the power to veto a proposed use. This results in an *underutilization* of the resource. Heller thinks the problem is that property rights have been partitioned into pieces that are too small.[17] The medieval peasant owned a right to the residual income of his strips, as well as (in the main) the right to sell strips to other peasants. But many pieces were sliced off the fee simple ideal, including the right to graze animals on the land in fallow years. Coase and Demsetz teach that, in the absence of transaction costs, rights cut too thin will quickly reassemble into optimal bundles. But if there are transaction costs, the rights may reassemble only with difficulty. Heller's examples include the granting of thinly chopped rights in the transition economies of Eastern Europe as well as some cases in intellectual property (Heller and Eisenberg, 1998).

In the property rights tradition, the theory of the firm is simply an application of the theory of the coalescence of property rights. Although it is seldom clearly spelled out, the starting point for analysis is typically a world of completely modular atomistic production: each stage of production consists of an individual who owns the necessary physical capital (tools) and who coordinates his or her actions with other stages of production through an arm's-length transaction. Why is not all production carried out this way? Coase's (1937) famous answer is that there is a (transaction) cost to using the price mechanism. If transaction costs are the costs of a bad modularization, what can go wrong with the atomistic modularization?

One early answer pursued the analogy with property law: the problem with the atomistic modularization is that, under some circumstances, there are externalities among the property owners that are best accounted for by the coalescence of property into one set of hands. In a famous example, Alchian and Demsetz (1972) suggest that, if production requires teamwork, and team work means that workers cannot cheaply observe one another's marginal product, then private incentives to shirk will generate a tragedy of the commons. A realignment of property rights solves the problem, as all but one of the teammates lose their residual-claim status and become wage earners; the remaining individual ceases to be a team member but specializes in monitoring, and is monitored in that task by his or her residual claim.

This formulation focuses on the incentive aspects of property, and it takes ownership to be equivalent to a claim on residual income (Foss and Foss, 2001). Another view, originating as early as Coase (1937, pp. 391–392), sees ownership as involving not residual income streams but *residual rights of control*. Oliver Hart (1989) and his coworkers have lately championed this approach in a series of formal models. Because of uncertainty, no contract can foresee all

[17] There seems to me a distinction between saying that rights have been cut into too many pieces and saying that restrictions have been placed on a right. (This latter is the definition adopted in an illuminating analysis of the anticommons by Buchanan and Yoon (2000)). It is true that a restriction (a government land-use regulation, let us say) strips off a piece of the owner's right. But the piece stripped off is not necessarily in the form of a right that could in principle be tacked back on through exchange. In the cut-too-thin case, we would say that the system has been inefficiently modularized, and may or may not fix itself; in the restriction case, we would say that the system has been made less modular.

possible contingencies. Thus, there must be a residual right to make decisions in situations not covered by contract. That right is ownership, and ownership should be allocated to the party whose possession of it would maximize the joint surplus of production.[18]

In Hart's story, the criterion for allocating ownership boils down to a matter of incentives. The pattern of the ownership of tangible (non-human) assets will affect the incentives of the parties to cooperate with one another. By altering the parameters of the "game" the parties play, a reallocation of residual rights of control over packages of non-human assets can improve cooperation and increase joint surplus. But there are, it seems to me, other reasons why reallocating residual control rights can improve efficiency. One is simply differential knowledge, something never considered seriously in the formal models. Even if no one is worried about the possibility of "hold-up" or the expropriation of rents, it still may be worthwhile to assign to only one of the parties the residual control rights over a package of assets if that party has comparative advantage in making the decisions.

Frank Knight (1921) suggested that comparative advantage might arise if one party possesses the superior faculty of *judgment* (Langlois and Cosgel, 1993). But, *ceteris paribus*, genuine uncertainty—the prospect of or need for radical change—may by itself call for a consolidation of ownership. Stephen Littlechild provides one example.

> [I]f I am quite sure what kinds of actions my neighbour contemplates, I might be indifferent between his owning the field at the bottom of my garden and my owning it but renting it out for him to graze his horse in. But once I take into account that he may discover some new use for the field that I haven't yet thought of, but would find objectionable, it will be in my interest to own the field so as to put the use of it under my own control. More generally, ownership of a resource reduces exposure to unexpected events. Property rights are a means of reducing uncertainty without needing to know precisely what the source or nature of the future concern will be. (Littlechild, 1986, p. 35.)

There is also a flip side. Ownership may not only insulate one from certain kinds of unforeseen change, it may also enable one to *generate* radical change. I have tried to suggest on a number of occasions that concentrated ownership can overcome what I call the *dynamic transaction costs* of significant economic reorganization (Langlois, 1992b). This is a motive for vertical integration little noticed in the literature.

These issues are important for the discussion to follow. But before turning to them, let me complicate matters a bit. Harold Demsetz has recently criticized Hart's approach for focusing too narrowly on *residual* of rights of control. "I should think that an asset would be 'owned' by the person who finds ownership most valuable," he writes, "but the value of the asset derives from the value of all rights in it and not just form residual control rights" (Demsetz, 1998, p. 448). Moreover, rights of control—even residual ones, he thinks—can in fact be parceled out to the same extent as can rights to use or rights to income streams. For Demsetz (1998, p. 451), the only difference between ownership of the residual rights of control and rental of those rights is that the former is a holding in perpetuity. In defense of Hart one might respond: can one ever really contract away genuine residual control rights, even temporarily? No matter how much discretion I am granted in a contract, there are some

[18] For a related analysis more clearly influenced by the original property rights school, see Barzel (1987). For a discussion of the differences between the Hart and Barzel approaches, see Foss and Foss (2001).

decisions I cannot make in response to unforeseen circumstances if I am a renter. A rental contract that allowed me to sell or destroy the asset over which I have control would be indistinguishable from a transfer of ownership. In the end, perhaps, residual control cannot be separated from the holding of control rights in perpetuity.

Nothing brings out the difficulties with the concept of ownership more clearly than does the modern public corporation. Who owns the corporation? Henry Hansmann (1996) makes a good case that it is the suppliers of capital, the holders of common stock, who possess a claim to residual income as well as some abstract or high-level rights of control. On the other hand, most of the day-to-day rights of control rest in the hands of hired managers. Demsetz has argued that managers are thus the de facto owners, since effective control is largely in their hands. “What shareholders really own are their shares and not the corporation” (Demsetz, 1967, p. 359). From the point of view of theory, I tend to side with Hansmann and Hart. The shareholders “own” the corporation because they have the final say: managers cannot change the nature or strategy of the corporation in a radical way without the consent of stockholders, just as the renter cannot change without consent the use to which he puts Littlechild’s field. From a pragmatic point of view, however, both are correct, in the sense that, in order to understand the corporation (and organization in general), we need to understand how and why decision rights are partitioned in collaborative enterprise.

Jensen and Meckling (1992) agree that the concept of ownership must involve not only the possession of decision rights but also the right to alienate those decision rights. Granting an individual both control and alienability is clearly a more complete modularization than granting control alone, since the owner with alienability needs to engage in less explicit coordination with others to use the asset effectively under all circumstances. In economics terms, it is alienability that solves both the problem of knowledge decentralization and the problem of incentives: the asset may be placed under the control of the person whose knowledge best equips him or her to use it, and alienability disciplines the owner’s use of the asset by making its value (to which the owner has a residual claim) measurable on a market.

This is the basic modularization of the market economy. It accords well with the modularization G. B. Richardson (1972) suggested in offering the concept of economic *capabilities*. By capabilities Richardson means “knowledge, experience, and skills”(1972, p. 888), a notion related to what Jensen and Meckling (1992) call “specific” knowledge and to what Hayek (1945) called “knowledge of the particular circumstances of time and place.” For the most part, Richardson argues, firms will tend to specialize in activities requiring similar capabilities, that is, “in activities for which their capabilities offer some comparative advantage” (Richardson, 1972, p. 888).

So why do not we observe everywhere a perfectly atomistic modularization according to comparative advantage in capabilities—with no organizations of any significance, just workers wielding tools and trading in anonymous markets? We have already seen the outlines of several answers. The older property rights literature, we saw, would insist that the reason is externalities, notably the externalities of teamwork arising (for example) from the nature of the technology of production itself. The mainstream economics of organization is fixated on another possibility: because of highly specific assets, parties can threaten one another with pecuniary externalities ex post in a way that has real ex ante effects on efficiency (Klein et al., 1978; Williamson, 1985). Richardson offers a somewhat different, and perhaps more fertile, alternative. Firms seek to specialize in activities for which their capabilities are *similar*; but production requires the coordination of *complementary* activities. Especially in a world of change, such coordination requires the transmission of information beyond what can be sent through the interface of the price system. As a consequence, *qualitative coordination* is necessary, and that need brings with it not only the organizational structure called the firm but also a variety of inter-firm relationships and interconnections as well.

Whichever story one chooses, organization (in the broadest sense) arises as a nonmodular response to the fact of, or the need for, interactions among the modules. Organization is always a demodularization and repartitioning that severs the right of alienation from at least some of rights of decision. And, in all cases, the technology of production both causes and shapes the resulting nonmodular interconnections.

6. Modularity, organization, and technology

Sanchez and Mahoney (1996) contend that *products design organizations*. What they mean by this, roughly speaking, is that nonmodular products lead to or are best produced by nonmodular organizations, whereas modular products call for modular organizations. In a sense, however, this is a variant on what the mainstream economics of organization has long believed: *production processes design organizations*. If the production process requires team production or calls for highly specific assets, a nonmodular structure ("hierarchy") is in order; otherwise, a modular structure ("the market") is more appropriate.

In the case of Sanchez and Mahoney, at least, the notion that technology designs organizations is probably not as deterministic as it sounds. One can easily give the idea an evolutionary spin. Technology designs organizations in the same sense that the arctic designed polar bears: the bears emerged as structures well-enough adapted to, and therefore reflecting the nature of, the environment they faced. In my view, however, even this interpretation is too strong. In the case of technology and organization, sometimes polar bears can design the arctic.

On the one hand, it is true, for example, that IBM had to reinvent itself when it introduced the 360 line of computers in the 1960s (Langlois, 1997). IBM had been a master of architectural innovation, able to recombine standard components to fit the customer's computing needs. Because of the bottleneck of writing software for many incompatible systems, however, the company chose a dramatically different strategy in introducing what was essentially a modular system. The 360—referring to all the points of the compass—was a single basic system that, through modular recombination, could serve all purposes. Significantly, IBM adopted a distinctly nonmodular organizational structure to manage the 360, although this may have to do with the fact that the 360 was an exclusively *internal* modular system: IBM worked hard to keep interfaces proprietary and to prevent others from supplying compatible modules.

On the other hand, however, vertically integrated computer companies in the 1970s and 1980s kept trying to build personal computers on the nonmodular (or internally modular) model, not because personal computers ought to have been designed that way, but because the imperatives of organization insisted.[19] This is even true of Apple, which persists in building computers with less modularity than the competitors and (at least until recently) with very little external modularity at all (Langlois, 1992a).

The automobile industry provides a number of interesting lessons about modularity and nonmodularity in organization and technology.[20] Before the Model T, car manufacture was a highly modular enterprise; car makers were assemblers buying standard or easily modified parts from subcontractors. In this context, Henry Ford's invention of the moving assembly line and other high-volume production techniques was a remodularization of the manufacture of automobile parts. Ford and his engineers were inventing the process as they went along, and interfaces were necessarily in flux. Because of this, Ford needed authority and scope of action to bring about radical change quickly. By owning most of the stages of production, he was able to experiment with new techniques without paying the dynamic transaction costs of bringing outside players into the process.[21] Once the process of mass production crystallized, however, and change slowed, Ford realized that he could (re)decentralize production, albeit within the confines of the Ford organization.

As I mentioned earlier, Ford's finely tuned nonmodular structure of production did not adapt well to a world in which used cars began to compete with the undifferentiated Model T. General Motors responded to this challenge with a structure that was more modular, both in terms of the modular divisional structure of the M-form (Chandler, 1977), but also in terms of a platform-based production strategy that allowed product differentiation and annual model changes while still taking advantage of large production runs for common components (Raff, 1991).

Nonetheless, from the 1930s on the American industry adopted on the whole a highly nonmodular structure of production. Consider the relationship between manufacturers and parts suppliers. In the American industry, suppliers were treated at arm's-length, with price a crucial point of negotiation. Successful bidders would be presented with detailed specifications, and would have no role in the design of the parts they produced let alone in the design of the overall automobile. Now, one could think this system modular in that it relied on the interface of the price system and required only a lean transmission of information between manufacturer and suppliers. In fact, however, this is clearly nonmodular from the point of view of design and production, since it centralized all design decisions and accorded supplies no protected sphere of authority—no competency in execution and no hidden information. Suppliers could not be trusted to vary designs, since any changes would ramify dysfunctionally through the intertwined design and production of the automobile.

One of the central facts about the automobile industry in the last 15 years or so is that this contracting structure has changed. Influenced by Japanese methods of production and design, American firms have begun to adopt long-term relationships with suppliers that

[19] IBM itself originally tried to adapt organization to design by creating a small near-autonomous division to develop the original PC. But the company squandered its lead in the market because it could not subsequently fight the temptation to what Williamson (1985) calls "selective intervention," that is, the tendency to meddle with autonomous units. The result in this case was a series of idiosyncratic models that failed in the market.

[20] The next few paragraphs draw on Langlois and Robertson (1989).

[21] I have suggested elsewhere that the need for authority during periods of rapid remodularization often gives rise to the (highly nonmodular) form of organization Max Weber described as *charismatic authority* (Langlois, 1998). Schumpeter called this entrepreneurship.

involve genuine collaboration (Womack et al., 1990). Some commentators have played up the collaboration angle, suggesting that this successful new organizational response works because it eliminates the modularity of the market in favor of a nonmodular structure of intense communication of information. For example, Helper, MacDuffie, and Sabel appear to see the matter exactly this way. Commenting on the new collaboration among manufacturers and suppliers in automobiles, they write:

> This activity is not supported by clearly-drawn property rights: It is usually impossible to say who owns partly-finished designs, or the rights to determine use of a resident engineer's time, etc. Nothing suggests that dealings are governed by elaborate (relational) contracts—often considered a substitute for vertical integration as a governance mechanism—that distribute the burdens between the parties in case of a long list of contingencies and provide for arbitration in the case of disagreements. Rather, the response to problems is . . . to try and solve them together (Helper et al., 2000, p. 473).

As I argued earlier, ambiguous boundaries are always necessary to some extent when learning is taking place. And neither manufacturer nor supplier may own complete (alienable) decision rights at any point in the process.

But it would be a mistake, I think, to read the essence of the new collaboration in automobiles as arising out of a demodularization in which encapsulation has been eliminated in favor of intense communication. Quite the opposite is the case. What distinguishes the new American collaboration, like Japanese collaboration before it, is *increased modularity*. Rather than handing suppliers detailed instructions, manufacturers now give suppliers interface specifications and then encourage them to design the parts as they see fit. So called first-tier suppliers may even be ceded authority for major components of the automobile (Womack et al., 1990). Although some collaboration and exchange of general knowledge takes place, the underlying design parameters of each part become hidden information from the perspective of the manufacturer.

7. A modularity theory of the firm?

Here, then, is the modularity theory of the firm. Firms arise as islands of nonmodularity in a sea of modularity.[22] They may do so in response to externalities arising from the likes of team production or asset specificity. More interestingly, firms may also arise in order to *generate* externalities, that is, to facilitate the communication of rich information for purposes of qualitative coordination, innovation, and remodularization. Hybrid forms like joint ventures and collaborative arrangements arise for similar reasons.

The notion that firms may come into being in order to create externalities requires some elaboration. Quite a number of writers have argued that the firm exists because it offers a special kind of information exchange that somehow generates more knowledge than the "sum" of the knowledge of the participating individuals (Aoki, 1990). Thus, the web of externality and thick communication within the firm has benefits that outweigh those of

[22] To put it more precisely, firms (and other organizations) are partitions of decision rights, alienability rights, and residual claims alternative to an atomistic modularization in which all three coincide.

greater decentralization. Many, indeed are impressed with the almost mystical collectivist benefits of the firm as an institution, benefits allegedly arising from trust and commitment[23] (Hodgson, 1998). “Firms exist,” in this view, “because they provide a social community of voluntaristic action structured by organizing principles that are not reducible to individuals”[24] (Kogut and Zander, 1992, p. 384).

The approach from modularity is not inconsistent with this view. But some cautions are in order. For one thing, most if not all of the benefits claimed for social communities within firms have also been claimed for social communities across firms, including both geographical industrial districts (Marshall, 1961; Saxenian, 1994) and “virtual” industrial districts of professionals (von Hippel, 1989; Savage, 1994). Qualitative coordination and learning are always matters of combining the knowledge and ideas—the capabilities—of a variety of individuals and groups, sometimes leading to an “emergent” result. The social network of a firm can certainly achieve this kind of cross-fertilization, but it is necessarily limited (*qua* firm) to the capabilities within its boundaries. Interfirm networks, and indeed markets, can also engage in knowledge combinatorics, a process that modularity helps along; and such interfirm networks are not limited in the capabilities they can address. Moreover, not all firms fit the picture of a social learning community; more than a few better fit the image of a Weberian bureaucracy in which roles are fixed and knowledge flows strictly channeled.

Where does this leave us? The idea that the essence of the firm is nonmodularity seems to me a robust one. But it is not clear that there is any simple theory of the nature and causes of that nonmodularity. This paper has tried to set out, in perhaps too desultory fashion, many of the necessary building blocks. Scholars can use these (and other) building blocks to understand the partitioning of decision rights, alienability rights, and residual claims in particular real-world organizational structures.[25] It is only fitting, after all, that the modularity theory of the firm should itself be a modular system.

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[23] An odd view of the firm indeed to readers of the Dilbert comic strip.

[24] For a critical perspective on this point, see Foss (1996a,b).

[25] I would offer as role models Dahlman’s (1980) analysis of the open-field system and Savage’s (1994; Savage and Robertson, 1999; Langlois and Savage, 2000) analysis of the professions.

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