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Where Do Transactions Come From?
A Perspective from Engineering Design

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Abstract

Our goal in this paper is to explain the location of transactions (and contracts) in a system of production. Systems of production are engineered systems, and where to place “transactions” is one of the basic engineering problems that the designers of such systems face. We begin by characterizing a system of production as a network of tasks that agents perform and transfers of material, energy and information between and among agents. We then argue that whereas *transfers* between agents are absolutely necessary and ubiquitous in any human-built system of production, *transaction costs* make it impossible for all transfers to be transactions. The particular transaction costs we are concerned with are the so-called “mundane” costs of creating a transactional interface: the costs of defining what is to be transferred, of counting the transfers, and of valuing and paying for the individual transfers. We go on to argue that the *modularity* of a system of production determines the system’s pattern of mundane transaction costs. In this fashion, the engineering design of a system of production necessarily establishes (1) where transactions can go; and (2) what types of transactions are feasible and cost-effective in a given location.

Key words: transaction — transaction cost — modularity — encapsulation — information flows — division of cognitive labor — network — engineering design

JEL Classification: D23, L22, L23, M11

Introduction

For the last thirty years economists have used the related concepts of "transaction," "transaction cost," and "contract," to illuminate a wide range of phenomena, including vertical integration, the design of employment contracts, the relation of a corporation to its capital providers, and the economic development of societies and nations.[1] The success of this work is clear, not only from the numerous theoretical insights it has generated, but also from the fact that these concepts are now essential parts of the working lexicons in the fields of business, law and organizational economics. However, if we shift our attention from the static analysis of existing products and firms to focus on the design of new products and new firms, the present conceptual framework and related analysis seem incomplete.[2]

Specifically to our purpose, although economists have explored the design of transactions and contracts in a wide variety of product-market settings, in the economics literature, there is generally assumed to be a pre-existing division of knowledge and effort that "calls for" a transaction of some type at a particular point in a production process. The models in this literature then compare, contrast and even "choose" between different forms of transactions, but they almost never question why the transaction occurs where it does. As a result, the forces driving the location of transactions in a system of production remain largely unexplored. Simply put: where do transactions come from? Why do they arise where they do?

Our goal in this paper is to explain the location of transactions (and contracts) in a system of production. Systems of production are engineered systems, and where to place "transactions" is one of the basic engineering problems that the designers of such systems face. Sometimes the

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[1] Ronald Coase's two seminal articles, "The Nature of the Firm" (1937) and "The Problem of Social Cost" (1960) established the foundations of the intertwined fields of transaction-cost economics and contract theory. Modern contract theory also draws heavily on the mathematical techniques of game theory, especially the contributions of Shapley (1953) and Selten (1978). It is impossible to cite adequately all important contributions to this widespread literature. However, on vertical integration, see, for example, Williamson (1985), Grossman and Hart (1986), and Baker, Gibbons and Murphy (2002); on the design of employment contracts, see Aoki (1988), Holmstrom (1982), and Holmstrom and Milgrom (1994); on contracts between a corporation and its capital providers, see Alchian and Demsetz (1972), Jensen and Meckling (1976), and Hart and Moore (1990, 1998); on the economic development of societies and nations, see North (1990), deSoto (2000), and Aoki (2001).

[2] Similar observations have been made by many other students of technological change and industry evolution, as well as by proponents of the Austrian school of economics. A short, very incomplete list of contributions in this vein includes Nelson and Winter (1982); Dosi (1984); Pavitt (1999); Langlois (2002).

laws of physics and logic, operating through a particular technology, make the location of transactions obvious. But at other times, the designers can choose whether to have a transaction or not. The decision to have a transaction (or not) in turn will affect the design of the non-transactional elements of the system. If the choice is to have a transaction, the work of "making" the transaction will have to get done. If the choice is not to have a transaction, the designers may have to compensate for what the transaction might otherwise have accomplished.[3]

In order to explain the location of transactions, we will first characterize a system of production as a *network of tasks* that agents perform and *transfers* of material, energy and information between and among agents. We will then explain what a transaction is (and is not), and what having a transaction entails for the network. We will argue, in fact, that whereas the agents' physical and cognitive limitations make *transfers* of material, energy and information between agents absolutely necessary and ubiquitous in any human-built system of production, *transaction costs* make it impossible for all transfers to be transactions.

The particular transaction costs we are concerned with are not the costs of agency and opportunistic behavior, which are classically the focus of transaction cost economics and contract theory. The costs that we will focus on are the more "mundane" costs[4] of creating a transactional interface: the costs of defining what is to be transferred, of counting the transfers, and of valuing and paying for the individual transfers. These costs, we will argue, are determined by the material, energy, and information flows embedded in the underlying system of production. At some points in the system, transfers are simple, and therefore, easy to standardize, easy to count, and easy to value. Mundane transaction costs are low at those points. At other places, transfers are complex, hence impossible to standardize, impossible to count, and impossible to value. Mundane transaction costs are high, and often prohibitive, at those locations.[5] We will go on to

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[3] In economic language, we are saying that a production function may change because of the presence or absence of transactions. Modern transactions cost and contract theory models provide for changes in the *inputs* to production (e.g. effort) and its *costs*. But such models do not contemplate changes in the production function itself.

[4] The term "mundane transaction cost" is due to Williamson (1985).

[5] Many contract-theory models are based on the axiomatic assumption that certain actions are "*ex post* observable but not 'verifiable,' hence not *ex ante* contactible." This assumption is usually justified on the grounds that the contingent behaviors are so complex that it is not worthwhile (i.e., cost-effective) to specify them in advance. These are cases in which, by assumption, the (mundane) costs of writing a "complete" contract are prohibitive.

argue that the *modularity* that is designed into a system of production determines the system's pattern of mundane transaction costs. In this fashion, the engineering design of a system of production necessarily establishes (1) where transactions can go; and (2) what types of transactions are feasible and cost-effective in a given location.

Before proceeding to the main argument, we should explain that our intentions in this paper are quite limited. We are seeking to connect the engineering design of a system of production, specifically its modularity, to its (mundane) transaction costs. Many of the connections we make will be obvious to most readers. We think this effort is worthwhile, however, because mundane transaction costs presently lie in the background of transaction costs economics and contract theory: they are taken so much for granted that they are simply not worth mentioning most of the time. In this paper, we will risk saying what is obvious in order to convert implicit knowledge about mundane transaction costs into explicit knowledge. In so doing, we hope to show that there are deep and interesting connections between two widely separated fields: transaction cost economics and contract theory and engineering systems design.

The Task and Transfer (T&T) Network

The basic unit of production is a *task*. Imagine all the tasks needed to produce all the goods in a modern economy. The tasks are linked by the logic of their underlying technologies. In particular, the outputs of some tasks are inputs to other tasks.

Tasks must be carried out by agents, including people and machines.[6] In human systems of production, even very primitive ones, no single agent is capable of carrying out all tasks, hence it is necessary to *transfer* various things from agent to agent in the system. Effecting transfers

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[6] It may seem odd to some readers to call machines "agents" in a system of production. However, we think the characterization makes sense. Like humans, machines perform many tasks and transfers in the system of production. Like humans, machines make decisions, indeed they are making increasingly complex and sophisticated decisions. And like humans, machines have physical and cognitive (i.e., information processing) limitations, which must be taken into account in designing a system of production.

adds a new set of tasks to the system, and thus transfers are costly. However, these additional tasks are essential given that all agents have both physical and cognitive limitations.[7]

Taken as a whole, the tasks, the agents who carry out tasks, and the transfers make up a vast *network* of productive activity. In this paper, we will call this network the "Task and Transfer" or T&T network. A functioning T&T network defines and performs tasks, including transfer tasks, and matches agents to tasks in such a way that the desired goods are obtained, and no agent has to carry out tasks that are beyond its ability. In modern economies, the totality of the T&T network is quite mind-boggling, but most of the time, we take its (relatively) smooth operation for granted.[8]

What Gets Transferred?

What gets transferred in the T&T network? First of all, materials and material objects get transferred from agent to agent through the great chain of production. For example, an automobile starts out as ores, petroleum, silicon, wood, wool, and trace elements. Through a series of tasks and transfers, these raw materials are transformed into components, which are then assembled into a highly articulated, complex artifact. Likewise, energy in various forms gets transferred from generators of energy to those points where the energy is needed.

Information also must be transferred among agents within the T&T network. In fact, it is useful to distinguish three types of information: data, designs, and "tags." Briefly, data is information about the world that must be received and interpreted by agents in order for the T&T network to function efficiently. Designs are solutions to problems posed by data. Tags are

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[7] On the design of tasks and transfers in a system of production and, especially, the level of detailed specification needed to achieve functionality and efficiency, see, Nevins and Whitney et.al. (1989) and Spear (1999, 2002). Also, the contents of tasks and the nature and location of transfers may change over time as agents learn and as new technologies introduce new agents (like computers) into the system. Thus, in addition to being finely structured, modern systems of production are inevitably dynamic. On the evolution of a manufacturing system, see, especially, Fujimoto (1999).

[8] A few economists, most notably Hayek (1945), have expressed wonderment at how well the network operates.

used to identify and locate resources and capabilities in the system. We expand on each of these definitions in the sections below.[9]

Data

Data includes such things as physical and biological facts, preferences, demands and prices. In general, single agents or small groups of agents cannot control data although they can (and often must) respond to it. And whereas materials can be thought of as flowing "down the chain" of production, data often flows "up the chain." For example, in a modern customized automobile assembly plant, an order for "a green sedan with a CD player and a sunroof" may be transmitted from a customer to a salesperson, and thence to a production scheduler (which may be a computer). The order and its details are data, which flow "upstream" in the T&T network. These data must first be transferred, then absorbed and interpreted by a capable upstream agent: the data can then be used to modify the "downstream" tasks of making a particular automobile.[10]

Money and *credit* are a special kind of data. Like other forms of data, money and credit generally flow "upstream" from the users of artifacts to the makers of artifacts. But, even though in modern economies, a money or credit transfer is "merely" a transfer of information (technically it is an entry in two accounting ledgers), such transfers must obey special rules, which limit the supply of money and credit. Thus, when the customer ordered the green sedan with the CD player and sunroof, she had to put a deposit down on it; when she took delivery, she either had to pay for the car immediately or enter into a binding agreement to pay for it over time. The car company thus obtained either cash or a financial claim, and the customer's ability to buy other goods for cash or with credit was reduced commensurately. Because money and credit

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[9] Economists recognize the centrality of information to the functioning of modern economic systems. However, the literature of information economics usually conceives of information as a "signal" arriving from the outside world. Often it is assumed that some agents receive the signal, whereas others do not, hence the information is "asymmetric." Because of their conceptual focus on signals, economic models tend to focus on data and data management and to ignore designs and tags. See, for example, Marschak and Radner (1972); Cremer (1980); Aoki (2001), as well as the Nobel Prize winning work of Vickrey (1961); Mirrlees (1976); Akerlof (1970); Spence (1973); and Stiglitz (1975).

[10] This stylized example has been informed by the work on "build-to-order" systems, flexible supply chains, and mass customization by Fine (1998), Fujimoto (1999), Pine (1999), and Spear (2002),.

are in limited supply, they are an appropriate means of recording, storing and transferring generalized "value" from agent to agent in the T&T network.[11]

Designs

Designs are another type of information that gets transferred in the T&T network. Designs are algorithms, recipes, or processes.[12] The output of a design process is a solution to a problem (or set of problems) in the T&T network.[13] The solution in turn must conform to the laws of physics and logic, as well as to constraints imposed by the local conditions. Like materials, designs are inputs to production, hence flow "downstream." An assembly line which can "build to order" a green sedan with a CD player and a sunroof must be designed to address the problems of building to order and mass customization. Before the order was given, the line must have already incorporated designs to permit such flexibility.

"Tags"

Tags are the third and final type of information that needs to be transferred in a T&T network.[14] Tags identify positions in the network: they contain information about which agents are performing or can perform particular tasks or tranfers. Unlike data or money, which generally (though not always) flow "upstream," and designs, which flow "downstream," tag information gets tranferred both ways, on a "need to know" basis. Advertisements are tags, as are job descriptions and professional accreditations. Telephone numbers, email addresses and

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[11] The supply of money and credit needs to be limited but need not be fixed. Modern macro and monetary economics addresses the optimal management of the supply of money and credit. In developed economies such management is usually delegated to a central bank.

[12] Sorenson, Rivkin and Fleming (2002) argue that "knowledge" consists of algorithms and recipes. We agree that algorithms and recipes are subsets of human knowledge, but we are not comfortable characterizing all of human knowledge that way. We think "design" captures the idea of knowledge with a *specific* functional purpose. In contrast, the word "technology" captures the idea of general functional knowledge that has not (yet) been converted into a design. On design processes, especially the distinction between complete and incomplete designs, see Baldwin and Clark (2000), Chapter 2.

[13] The idea of a design as the solution to a problem was advanced by the influential design theorist, Christopher Alexander (1964). In his essay, "The Science of Design," Herbert Simon (1999, p. 111) put forward a similar idea, saying that designs are "courses of action aimed at changing existing situations into preferred ones."

[14] For a discussion of the role of tags in complex systems generally, see Holland (1996). The notion of tags is closely related to the concept of "information hiding," developed by David Parnas with respect to computer hardward and software design. See Parnas (1972a,b).

DNS identifiers are also tags. For example, the consumer who bought the green sedan first had to locate an auto dealer. She could do so by looking at the yellow pages, by using an electronic search engine, or by remembering that she had seen a dealer's sign on her way to work. Yellow pages listings, search engine links, and signs identifying places of business are all tags.

Decision rights and *property rights* are a special form of tag. Like money and credit, for such rights to be effective, they must be in limited supply. They establish who or what has the right to direct the T&T network at a particular point. For example, restrictions on physical processing capacity set an upper bound on the number of automobiles that a given assembly line can manufacture in a given time period. Thus the salesman who took the order for the green sedan had to relay it to a production scheduler, which was probably a computer (or a computer with human overseers). The scheduler in turn had to convey the order to the assembly line, taking account of other orders and the capacity of the line. Two schedulers for one line will create chaos, hence it is reasonable to give one scheduler the decision rights over a particular line.

Which agent has scheduling rights over a particular line is determined in a two-step fashion: first, socially binding property rights determine who gets to select the scheduler;[15] second, a particular scheduler with appropriate training (if human) or programming (if a computer) is designated for a particular line at a particular time.

Note the complexity of information flows even in this rather stylized example. First, the designation of a particular scheduler is part of the detailed *design* of the T&T network for an automobile. The design must take account of *data* about probable orders and the capacity of the line. The right to make the design decision is conveyed by property rights over the line: property rights are *tags*. Finally, the order-takers must know how to submit an order to the right scheduler (whom to contact; what to include in the order). The ordering procedure is a *design*; the order itself is *data*; the information on how to contact the scheduler is a *tag* read by the order-takers. But the scheduler also must have information about which agents are allowed to submit orders, hence the order-takers must have *tags*, too, which can be read by the scheduler. All of these

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[15] On property as a "bundle" of decision rights including the right to determine use, see, for example, Demsetz (1967); Alchian and Demsetz (1973), Posner (1977), and Grossman and Hart (1986). For a historical review and critique of this concept, see Grey (1980).

information transfers necessarily swirl around the system of material and energy transfers that make up the modern assembly line of an automobile.[16]

In summary, transfers of information, material and energy are ubiquitous in the T&T network of production. The transfers are needed because there are limitations on the physical and cognitive capacities of both human beings and machines. And such transfers must take place in a complex, but logical order, in order to turn components like sheet metal and bolts, plastic shapes, glass, paint, and electronic equipment into complex but useful artifacts like a green sedan with a CD player and a sunroof. Therefore, the transfers, like the tasks between them, must be designed.

The tasks and transfers are not designed by any central planner or authority, however. They are designed by engineers and other system designers with local knowledge, local authority, and local incentives. Because of their own physical and cognitive limitations, the engineers and system designers perforce must work on subsets of the T&T network and on the interfaces between those subsets.

What Are Transactions?

Transfers within the T&T network are not necessarily transactions.[17] A transaction is more than a transfer: it is a transfer that is (1) counted; (2) standardized; and (3) compensated. Each of these conditions needs explaining.

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[16] Based on firsthand observation of several facilities, Spear (1999, 2002) describes in detail the information transfers implemented both within and across the manufacturing facilities of Toyota and some of its major suppliers. This example is a tiny but representative excerpt of his results.

[17] This may seem obvious, but many economists do not distinguish between transfers and transactions within a system of production. Coase (1937 reprinted in 1988), for example, implicitly conceives of production as a sequence or chain of invariant "transactions" which can take place within or across firms: "[A] firms will tend to expand until *the costs of organizing an extra transaction* within the firm become equal to the costs of carrying out *the same transaction* by means of an exchange on the open market or the costs of organizing another firm…. " (p. 44, emphasis added). Williamson (1985) says: "A transaction occurs when a good or service is transferred across a technologically separable interface. One stage of activity terminates and another begins." (p. 1.) However, Williamson does not describe "technologically separable interface," except to assert that such interfaces are common within the general system of production. Focusing on contracts, Grossman and Hart (1986) argue that there are eventualities and decisions that cannot be specified in advance ("non-contractible"). But their solution to this problem is to change the nature of the contract (the transaction) between the two parties, acknowledging that the best feasible configuration may be second-best.

To see how a transaction differs from a transfer, consider a generic transfer, wherein agent A conveys “X” to agent B, and B receives “X” from A.

$$A \xrightarrow{\text{“X”}} B$$

As we have said, in the T&T network, “X” may be a material object, energy, or information. We assume that B must have “X” in order to perform a task that is an essential step in a larger system of production. But, from a technical perspective, (1) A and B do not have to record the fact that a transfer has occurred; (2) A and B do not have to agree on what “X” is; and (3) B does not have to pay A for “X”. The transfer of “X” can be effective and productive even if none of these conditions is satisfied. However, we contend, the transfer cannot be a *transaction* unless all three conditions are satisfied.

For example, suppose “X” is a piece of information. B may obtain the information in a casual conversation with A. It is well known that information is non-exclusive, hence B having the information does not prevent A from having it, too. A may not even notice or remember that she transferred the information to B, and B may not remember where he got it. Next, if B can act on the information, its meaning for B will be different from its meaning for A. In a casual conversation, A and B do not have to agree on what B can, should or may do with the information transferred. Finally, B may be willing to pay for the information, but if A does not charge for it, B may get it for free. Hence, the transfer of information “X” can be effected without the transfer being counted, standardized, or paid for. This is true for material goods and energy as well: for example, when a host sets up a buffet table, material and energy are provided to the guests without counting the transfers (“how many potato chips did you take?”); standardizing them (“what does shrimp signify to you?”); or demanding payment (“red sauce is about to drip on your tie, what will you pay for a napkin *now*?”).

A transaction, we propose, is a transfer that is standardized, counted, and compensated.[18] Each of these steps is costly. Standardization requires a system for creating a

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[18] Under this definition, unilateral transfers, including gifts, inheritances, thefts, and advertisements, are not transactions. This accords with commonsense usage. The definition is also consistent with the concept of

common description of the transferred object among two or more parties. Counting requires a measurement system appropriate to the standardized definition; and compensation requires a system for valuing the transferred object and paying for it. Each of these systems—standardizing, counting, compensating—adds a new set of tasks and transfers to the T&T network. Thus it is costly to convert even the simplest transfer into a transaction.

However, the costs of counting and compensating vary dramatically across different types of transfers.[19] Transfers of discrete material objects are easier to count than transfers of fluids or energy. Because of the laws of conservation of matter and energy, transfers of matter and energy are generally easier to count than information transfers. Imprecise counting is cheaper than precise counting.[20] Finally, infrequent payments are cheaper than frequent payments.

The cost of "standardizing" a transaction, that is, arriving at a common description of what is being transferred, also varies across types of transfers.[21] It is easier to agree on simple descriptions than complex descriptions, and each party to agreement increases the cost. Thus B may hire A for X "days of work," but the two may agree to leave open the exact specification of what is to be done.[22] B will then have to count the days that A works, and pay A for those days,

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"reciprocal altruism" or "social exchange" in evolutionary psychology (cf. Cosmides and Tooby, 1992, p. 177).

[19] Some degree of standardization is a pre-requisite to counting and compensating, since one can only count objects in a given class or category. It is noteworthy, however, that economics, both classical and neo-classical, takes the existence of standardized "goods" as well as counting and payment methods as axiomatic. Implicitly, in supply-demand and general equilibrium models, there are always well-defined "goods" underlying every unit of Quantity (the count) that gives rise to a Price (the payment). Barzel, 1997, is a notable exception to this generalization, however, since he conceives of goods as fluctuating bundles of property rights.

[20] Old-fashioned inventory and cost accounting systems used in manufacturing and retailing relied on extremely imprecise counting methods, e.g., standard costs and annual inventories. Cf. Horngren, (1982). Today such systems are being replaced by automatic entry systems, barcodes, and scanners. These technologies have dramatically lowered the costs of precise counting.

[21] It was Coase's great insight that the apparatus of goods definition and counting, which underlies the pricing system, is neither automatic nor free: "The costs of negotiating and concluding a separate contract for each exchange transaction … must also be taken into account. Again, in certain markets, e.g., produce exchanges, a technique is devised for minimizing these contract costs; but they are not eliminated"(op. cit. p. 39). The technique Coase referred to was probably that of selling by the crate or the bushel. It is much more costly to count and assess the quality of each piece of produce than to count by larger lots and accept average quality within each lot. Traditionally one of the services provided by produce and grain exchanges was to define the standard weights and volume measures that determined lot sizes for transactions conducted within the exchange. On the difficulty of assessing the quality of complex things, see North (1990) and Barzel (1997).

[22] Cf. Coase (1937), Simon (1951).

but they can leave the bounds on what is to be done tacit (the cheapest form of description). If each stays within each other's expectations, the "days of work" description may be sufficient to support the transaction.

But if a disagreement is likely, then more costs will need to be incurred in order to arrive at a common description of the work or effort that will be transferred. The additional costs of standardization will arise before, during and after the work is done. Before the fact, there will be costs of modifying the contract to make the work description and the payment terms more precise. During the work, there will be costs of monitoring and measuring performance relative to the more precise work description. And after the fact, there will be costs of computing pay relative to the more precise description, and potentially costs of invoking contingent options, like nonpayment, termination, or litigation.[23]

If transactions are more costly than plain transfers, then why have transactions at all? An obvious answer, for economists, would be: "to improve incentives and thereby reduce opportunism."[24] That is true enough. But from an engineering design perspective, two additional facts are worth noting.

First, in any complex system, standardizing transfers, counting what is transferred, and even devising reciprocal payments for transfers can serve other purposes besides providing incentives to human agents. Standardizing interfaces and counting what flows across an interface are classic ways of managing complexity and coordinating large decentralized systems. And local compensatory "payments" or feedback are a brilliant device for maintaining resource balance (homeostasis) in a complex system; for providing prompt diagnosis, repair and triage; and for constructing a fault-tolerant, robust and incrementally extensible network. Thus we

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[23] Modern contract theory recognizes the *ex ante* cost of standardizing the description of a good or work to be done. However, the *ex post* costs of defining and measuring (i.e., counting) *what was actually produced* are not usually addressed. Implicitly, in the models, there is a point (a time and place) at which the value of what was done will be revealed. The mechansims that reveal *ex post* value are not usually specified. See, among others, Grossman and Hart (1986); Holmstrom and Milgrom (1994); Baker, Gibbons and Murphy (2002).

[24] Opportunism here includes free-riding, shirking, consumption of perquisites or private benefits of control, strategic, wasteful investments, holdup, misdirected effort, excessive risk-taking.

would expect to see—and we do see—"transactions," that is, standardized, counted and compensated transfers, arising in complex, decentralized systems with no human actors.[25]

Second, however, if standardizing, counting and compensating are expensive activities, and if transfers that are not transactions are also feasible, then part of the job of designing the T&T network is to *locate* transactions vis a vis non-transactional transfers. Where in the T&T network will transactions be most efficacious and least costly? What forms should transactions take in particular locations? And how does the presence of a transaction change or constrain the T&T network around it?

In order to answer these questions, we must consider the structure of the T&T network in more detail. Specifically, we need a way to map the location of transfers of matter, energy and information within a complex T&T network. In this mapping effort, we will make use of a tool of engineering systems design, the so-called Task or Design Structure Matrix.

Mapping Transfers

An artifact must be produced before it can be used. In societies large enough to have a division of labor—which essentially means all human societies—the production of material artifacts can be separated from the use of those artifacts. The movement of an artifact from an individual producer to an individual user is, of course, a transfer. It is probably the most basic transfer in any economic system, and it is the paradigmatic transaction of economic theory.

It is noteworthy that the efficient transfer of a material thing from a producer to a user constrains the related transfers of information quite dramatically. The user cannot know everything about how the thing was made: if that information were necessary to the user, he would have had to produce the thing himself, or at least watch every step of production. The division of labor would then collapse. By the same token, the producer cannot know everything about how the thing will be used, for then she would have to be the user, or watch the user's

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[25] For examples, see Ashby (1960); Gerhart and Kirschner (1997), Chapter 4, "The Exploratory Behavior of Biological Systems"; Levy (1978) on the design of computer buses. Note also that the TCP layer of Internet protocols works by standardizing messages into "datagrams," counting the datagrams sent, and receiving acknowledgment ("compensation") for those that have been received.

every action. Thus, fundamental to the division of labor is a very substantial partition *and hiding* of information.[26] The hiding of information in turn supports a division of cognitive labor: the user and the producer need to be deeply knowledgeable in their respective domains, but each needs only a summary or abstract of the knowledge relevant to the other's domain.

The division of labor and information between the domains of production and use amounts to a *gateway* in the T&T network. To fix idea of a gateway and to introduce our mapping tool, the task structure matrix, let us consider the production and use of an iron pot hook in a pre-modern setting, when the making of wrought iron artifacts was still a craft. We chose this example because it illustrates team effort in each domain and a team-to-team transfer: from a smithy to a kitchen.[27]

Even in very primitive settings, working with iron requires a division of labor: there are many tasks that must be carried out simultaneously in order for the metallurigical processes to work. Hence the production of iron artifacts has always required multiple pairs of hands and eyes: an efficient team might range in size from two to six.[28] The same was true of cooking, although in pre-modern times, kitchen teams, especially in wealthy households, often had more than six members.

As an example, let us assume that there are five persons on the smith's team <S1,…, S5>, and five on the cook's team <C1,…, C5>. The tasks of iron-making are multifarious and interdependent. Hence, if we were to drop into the smith's establishment and record all transfers of material, energy, and information, the resulting graph would be bi-directional and complete: every member of the smith's team, no matter how lowly, would at some point give material, energy, or information to every other member. Symmetrically, every member would at some

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[26] The term "information hiding," is due to Parnas (1972a,b). For other references, see footnote 47 below.

[27] In 1750 and before, kitchens contained many wrought iron artifacts which were made by smiths. These implements included: brackets; pot-hooks; handles; spits; trivets; gridirons; toasters; conjurors; girdleplates; hand-irons; tongs; fire-shovels and dripping pans. See *Iron in the Service of Man* (South Yorkshire Industrial History Society) http://www.top-forge.fsnet.co.uk/Books/Service.htm, viewed 7/4/02. Smiths did not make pots, however. Pots and other cast iron implements were made at larger ironworking establishments, like the Saugus Iron Works, which operated in the Massachusetts Bay Colony from 1646 to 1688. See: http://www.cr.nps.gov/nr/twhp/wwwlps/lessons/30saugus/30setting.htm, viewed 7/4/02.

[28] In 1640, Top Forge, a wholesale ironworks in Wortley, England, contained "one hammer, one finery hearth one chafery hearth, and bellows for the hearths. A visitor in 1640 might see the hammerman , a boy and a man at the finery hearth, and two men at the chafery hearth. The team produced three tons of wrought iron in a good week." *Iron in the Service of Man*, op.cit. viewed 7/4/02.

point receive material, energy or information from all other members. The same is true of the kitchen team.[29]

Pot hooks and other wrought iron implements form a bridge between the two establishments. They are the products of the smithy and the tools of the kitchen.

We can represent the local T&T network made up of the smithy and the kitchen using a mapping device called a "task structure matrix" or TSM.[30] First, we list the members of each team along the row and columns of a square matrix. Then, if agent i transfers material, energy, or information to agent j, we place an "x" in the column of agent j and the row of agent i. The results of this mapping are shown in Figure 1. The dense web of transfers of material, energy and information *within* the smithy and the kitchen show up as blocks of "xs" in the matrix.[31] But between the two establishments, there is only one point of interaction: the transfer of a completed implement, in this case a pot hook.

The TSM shows that the system of production contained in the smith's establishment and the system of use contained in the cook's establishment are almost, but not quite, independent. The two subsystems are *materially connected* by pot hooks and other iron implements, which are made in the smithy and used in a kitchen. They are *informationally connected* by a set of common definitions of pot hooks and other iron implements. As long as the smiths and the cooks agree on what a pot hook, or a spit, or a gridiron is, the two establishments can support one another

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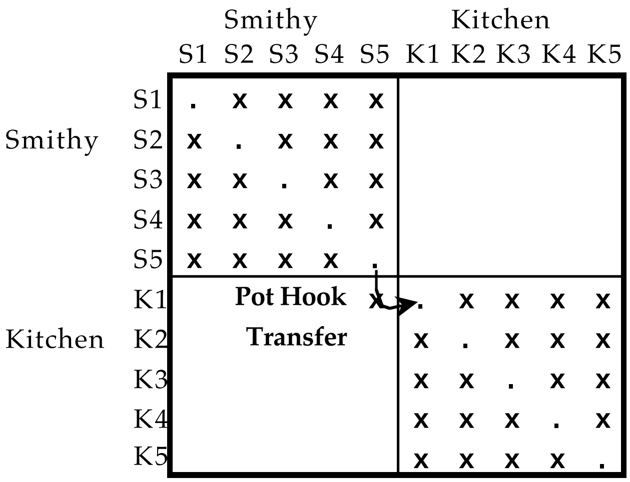
[29] Our example has been deliberately constructed to reflect the definition of team production put forward by Alchian and Demsetz (1972): "Two men jointly lift heavy cargo into trucks…. With team production it is difficult, solely by observing total output, to either define or determine *each* individual's contribution to this output of the cooperating units. The output is yielded by a team, by definition, and it is not a sum of the separable outputs of each of its members" (p. 779). This characterization applies to both the smithy and the kitchen in our example. On the use of graphs to represent dependencies (transfers) in production processes, see Kusiak (1995).

[30] Herbert Simon, in his classic article "The Architecture of Complexity" (1962, reprinted in 1999), may have been the first person to represent the interdependencies of a complex system via a square "causality" matrix. Independently of Simon, Donald Steward (1981) developed techniques for mapping the actual design parameter and task interdependencies of engineering projects. These techniques have been applied and extended in many different contexts by Steven Eppinger (1991) and his colleagues (cf. http://web.mit.edu/dsm/). Kusiak (1995) gives an excellent description of DSM mapping techniques. We have used this methodology map the structure of complex computer hardware and software designs (cf. Baldwin and Clark, 2000). Sharman et. al. (2002) have used it to map alternative structures for electric generators. In related work, Rivkin and Siggelkow (2001) use interdependency maps, expressed as matrices, to investigate the properties of different organizational structures.

[31] By recording only the presence or absence of transfers, the matrix abstracts from the true complexity of the actual system of production. To capture the whole process, the matrix would have to show: (1) what

without a lot of ongoing interaction. Hence this particular subset of the T&T network displays an extreme and almost perfect division of cognitive labor. The cooks do not have to know how to make pot hooks, and the smiths do not have to know how to make stew.

Figure 1
T&T Network for a Smithy, a Kitchen and an Iron Pot Hook



		Smithy					Kitchen				
		S1	S2	S3	S4	S5	K1	K2	K3	K4	K5
Smithy	S1	.	x	x	x	x					
	S2	x	.	x	x	x					
	S3	x	x	.	x	x					
	S4	x	x	x	.	x					
	S5	x	x	x	x	.					
Kitchen	K1			**Pot Hook**		x	.	x	x	x	x
	K2			**Transfer**			x	.	x	x	x
	K3						x	x	.	x	x
	K4						x	x	x	.	x
	K5						x	x	x	x	.

Locating Transactions

It is also relatively easy to turn the completed-pot-hook transfer into a transaction. Completed pots hooks are discrete material objects, thus easy to count. As indicated, a smith and a cook can agree on what a pot hook is, and its salient features (size, thickness, shape), hence the transfer can be standardized. And cooks value completed pots hooks, hence are willing to pay for them. When the pot hook is completed, moreover, its physical and energetic characteristics are stable: it is does not require special handling as is the case earlier in the production process. Also, the information that must be transferred from the producer to the user is minimal, amounting to the structural features of the pot hook itself. In contrast, a purchaser would need a lot more

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specifically will be transferred; (2) under what conditions each transfer will occur (because many transfers are contingent); and (3) whether each transfer is an essential part of the process or a byproduct.

knowledge, not to mention special equipment, in order to turn a bar of pig iron into a completed pot hook. Thus a bar of pig iron or an otherwise incomplete pot hook is not worth very much to a cook.

Obviously, the completed-pot-hook transfer point shown in the diagram is the "natural" or "least cost" place to locate a transaction in this T&T local system.[32] But what does it mean to be "natural" or "least cost"? Visually the transfer point looks like a bottleneck in the TSM matrix: it is the narrow point between two blocks. Substantively, we have seen that this means there are many, complex transfers of material, energy and information that need to take place within each establishment, and only a few, relatively simple transfers that need to take place between the two establishments. Thus, in contrast to production bottlenecks, which usually detract from efficiency, the completed-pot-hook transfer "bottleneck" supports an efficient division of cognitive labor by creating a narrow "gateway" where low-cost transactions can take place between the smithy and the kitchen.[33]

The best place to locate the transactional "gateway" is obvious. Pushing a transaction backward into partially completed pots hooks or forward into food preparation would require new, more complex systems of counting, and new, more complex definitions of pot hook (molten pot hook, a pot hook with jagged edge, a pot hook plus an onion, a pot hook plus a pot of stew). Moreover, if pot hooks were delivered incomplete, cooks would need to learn the smiths' craft and do the smiths' work; if pots hooks were delivered with ingredients, or cooked meals, the smiths would have to learn the cooks' craft and do the cooks' work. In effect, if the transaction is located at any other transfer point (and there are literally thousands of transfers points in the smithy and the kitchen respectively), then the two information sets, which can be made almost disjoint in the T&T network, must overlap in one establishment, and in the minds of some members of that establishment. And in a system made up of agents who are physically and

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[32] We believe that points like this one in the T&T network, where transfers are countable and information sets almost disjoint, are what Williamson (1985) was referring to when he used the phrase "technologically separable interface."

[33] Notice that material, energy, and all three kinds of information (data, design, and tags) must pass (be transferred) through the transactional "gateway." However, in order to have a cost-effective transaction, transfers through the gateway must be as simple as possible: simple enough to be standardized, counted, valued, and paid for.

cognitively limited, unnecessary overlaps of knowledge and processing capacity are wasteful and inefficient.

Why have any transaction at all? First, in a very small economy, like a manor or a plantation, transfers from the smiths to the cooks would probably not be transactions. The smiths would make iron implements, based on requests and perhaps detailed instructions from the kitchen, and they would give the finished artifacts to the cooks.[34] But in a larger economy, a transaction becomes a useful *lateral* coordinating mechanism. Even though their physical efforts and information sets are almost disjoint, the cooks and the smiths still need to be coordinated in terms of how many and what types of iron implements the one will buy and the other will supply. Placing a transaction—a shared definition, a means of counting, and a means of payment—at the completed-pot-hook transfer point allows the decentralized magic of the price system to go to work. Given a shared definition of pot hook, a means of counting and a means of payment, the cooks and the smiths can each know the price of a pot hook. They can compare that price to the cost of making the pot hook (the smiths' calculation) and the cost of other cooking devices (the cooks' calculation). If the price is high enough, the smiths may then be motivated to make pot hooks, and rewarded for doing so; at the same time, if the price is low enough, the cooks may be motivated to buy pot hooks and make stew (instead of spit-roasted meat, perhaps). The price of pot hooks thus serves as a signal to producers and users alike: it becomes *data* in the T&T network. And the transfer of money (or other consideration) from the cooks to the smiths serves to keep the T&T network as a whole in a resource balance. Economists have marveled at the workings of this decentralized, self-balancing, adaptive system since Adam Smith first described its properties over two hundred years ago.

Encapsulating Blocks of Transfers

We have seen that, if transactions are desirable, then the "natural" or "least-cost" places to locate them are those places where (1) standardizing and counting what is being transferred is

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[34] This is an instance of Stigler's (1951) general observation that small markets call for vertically integrated production. See footnote 39 below.

relatively easy and inexpensive; and (2) the common information needed on both sides of the transaction is least, i.e., the division of cognitive labor is greatest. When those two characteristics are combined, as at the completed-pot-hook transfer point, the location of the transaction is obvious. The decision appears trivial; any other location seems absurd.[35]

However, in complex production systems, many transfers of material, energy and information are not standardized, difficult to count, and of ambiguous value to the finished product. In general, the less standardized, the more difficult to count, and the less consistently valuable the transfers, the more difficult and expensive it will be to make such transfers into transactions. For example, what is the value of the master smith watching an apprentice shape a pot hook on a forge? Watching creates a transfer of data from the apprentice to the master smith. The transfer is costly: watching prevents the master from doing other things. The value of this transfer, however, is contingent. If the apprentice makes no mistakes, then the value of watching will be relatively low, although not zero. (The master can certify that the job was done properly, and also appraise the skill and effort of the apprentice.) However, if the apprentice errs, the master can intervene in the process, thereby initiating a transfer of material, energy and (design) information. In so doing, the master may save the artifact and teach the apprentice how not to err in the future. Constructing transactions that mirror the complexity of this set of contingent and interdependent transfers is practically, if not theoretically, impossible.[36]

Fortunately, humans have devised ways to effect complex transfers without making each and every one a transaction. The basic strategy is to create a "transaction-free zone," and then use transactions to bring resources into the zone, and move products out of the zone. This strategy, which we will call "transactional encapsulation," was first described by Coase in his

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[35] On this subject, Williamson (1985) remarked, "One of the reasons, I submit, why these mundane matters go unremarked is because most of us have reasonably good transaction cost intuition."

[36] Arrow (1964) and Debreu (1959) created a theoretical price system spanning all contingent transfers no matter how complex or microscopic. The costs of standardizing, counting, and arranging payments for complex, yet microscopic transfers are what prevent the Arrow-Debreu economy from becoming a real economy.

pathbreaking article, "The Nature of the Firm," in 1937. It lies at the heart of the modern theory of the firm.[37]

The basic encapsulation strategy works as follows: First, an agent or agents must identify a *group of tasks and transfers* involving multi-directional flows of material, energy and information. Such interdependent groups of tasks and transfers arise in many systems of production: they show up as *blocks* in a task structure matrix. The activities of the smiths formed one such block, the activities of the cooks formed another. The interdependent tasks and transfers then get lumped together: that is step 1 in the encapsulation procedure.[38]

Step 2 is to bound this group of tasks and transfers. By definition, any group of tasks and transfers is a subset of a larger T&T network. By design, transfers within the established boundaries will be complex and therefore have relatively high mundane transaction costs. Such transfers cannot be cost-effectively converted into full transactions. Instead of forcing these complex transfers to be transactions, encapsulation serves to create a local, bounded "transactions-free zone" in the T&T network.

Step 3 is to bring agents and resources into the *encapsulated local system*, and move products out of it. In modern economies, this is done by means of imperfect, but cost-effective transactions and contracts. Some of these transactions may be relatively straightforward to locate and design. For example, supplies, like pig iron, can be purchased, and products, like pothooks, can be sold. As we saw above, the physics and logic of the system of production may determine mundane transaction costs in such a way that the optimal locations and forms of some transactions are obvious.[39]

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[37] The strategy is similar to that which Aoki (2001) labels "informational encapsulation." However, Aoki's focus is on *what* gets encapsulated (information), whereas, in this paper, we are concerned with *how* encapsulation takes place (through transactions). Also, transactional encapsulation applies to all types of transfers—material, energy and information—not just information. Indeed material objects are generally the first things to get encapsulated via property rights (see Grossman and Hart, 1986, and Hart and Moore, 1990). Langlois (2002) also discusses encapsulation boundaries, with a particular emphasis on what it takes to maintain coherence in the task partition.

[38] Before the advent of electronic communications technology, "lumping together" meant colocating the agents who would perform the inter-related tasks and transfers in a specific work place. It is no longer necessary for agents to be physically colocated in order to perform complex interdependent tasks. Virtual colocation, mediated by high-speed information and energy transfers, may suffice for some systems of production.

[39] Nevertheless, the optimal location of supply contracts may change over time. For example, in his classic paper on vertical integration, Stigler (1951) argued that in small markets, enterprises would incorporate the

Arrangements with suppliers of labor and capital are usually trickier, however. In modern economies, these arrangements must be transactions in their own right.[40] Something, e.g., effort, will be transferred; it must be standardized in some fashion; it will be counted in some fashion; and it will be compensated in some fashion. The key phrase here is "in some fashion." By definition, precise counting, standardization, and compensation are impossible (or at least prohibitively expensive) for transfers within the encapsulated local system. Hence, transactions that bring agents and capital across the boundary cannot perfectly reflect the value of what is happening inside.[41] Fortunately, however, the boundary transactions only have to be "good enough."

There are, in turn, two tests of "good enough" (they are really one test, but it is helpful to divide it into two parts). The first test is: are the contract terms offered to suppliers or material, energy and information good enough to bring the resources needed into the encapsulated local system? The second is: is the encapsulated local system *financially sufficient*, that is, can it pay its suppliers according to their contracts, and have something left over? If the answer to these two questions is "yes," then the encapsulated local system can survive in a larger "free" economy.[42] The larger economy in turn spans the entire T&T network of a particular time and place, including all the encapsulated local systems, and the interfaces between the local systems.

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production of subsystems within the boundaries of a single firm. However, as the market grew larger, he conjectured, activities related to the production of subsystems would be spun off, becoming the basis of separate firms. The motivation for spinning off the production of subsystems was to obtain the benefits of scale economies in the manufacture of subsystems. The process Stigler described is a form of modularization (see below), however, he did not go into the mechanics of how to split a complex production process.

[40] In pre-modern economies, transactions were not commonly used to bring labor and capital into encapsulated local systems. Labor would often enter a local system by birth, adoption, capture, or bondage; capital was obtained through savings or inheritance, in fief, or as part of another transaction (e.g., supplier credit). For descriptions of various pre-modern arrangements for obtaining labor and capital, see, for example, Greif (1994, 1998); North (1990); as well as Southern (1953); Bloch (1961); Braudel (1982); Johnson (1991); and Favier (1998).

[41] Given the inherent imperfection of employment and capital contracts, it is not surprising that much of the modern literature in organizational economics and contract theory focuses on these transactions.

[42] By "free" economy we mean one in which encapsulated local systems can be created *at low cost* by *local agreements* between and among individual agents. In effect, agents have must have the ability to create associations, subject to financial sufficiency constraints. The rights of association do not have to be formal or legally constituted, but they must be effective, *de facto* rights. Many traditional and communist societies do not (or did not) give rights of association to their members (Shleifer and Vishny, 1994). Others have restricted those rights to subsets of the population (e.g. free men but not slaves, serfs, or women). Still others have conveyed theoretical rights of association to their members, but have made such associations prohibitively expensive to set up or maintain. See, for example, Khanna and Palepu (2000a,b); deSoto (2000); Djankov et. al. (2002).

The specific boundaries of an encapsulated local system can be designed to suit the needs of the particular system of production. Thus some non-transactional transfers, like telephone calls to suppliers or token gifts to customers, may take place across boundaries. Conversely, some formal transactions may take place within the boundaries, for example, employees may be required to pay for lunch at a company-owned cafeteria. There may even be subcapsules, i.e. divisions or departments, within an encapsulated enterprise, and standardized, counted, and compensated transactions between the subcapsules.

Nevertheless, the purpose of having encapsulated local systems in a larger system of production is to facilitate complex transfers without making them into transactions. (The Appendix describes the effects of encapsulation in complex systems generally.) Hence in a well-designed system of production, complex, contingent transfers with high mundane transaction costs will take place within encapsulated local systems. Transactions and contracts in turn will be used to bring resources into such systems and to transfer products out. In this fashion, the location of transactions and contracts serves to define the boundaries of encapsulated local systems in the larger system of production.

Firms are a form of encapsulated local system, thus the location of transactions and contracts perforce defines the boundaries of firms.[43] Indeed, firms can be considered as social artifacts *designed for the purpose* of encapsulating complex transfers of material, energy and information. Families, isolated villages, and nomadic tribes are also local systems that encapsulate complex transfers, but, in contrast to firms, their encapsulation is fortuitous: they are not (usually) created or designed for that purpose.

In summary, at any given time and place, the T&T network will have a structure, which can be made visible using the TSM mapping technique described above. From an engineering design perspective, *blocks* in the T&T network should be encapsulated, becoming what we have

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[43] Langlois (2002) makes a similar argument. His emphasis, however, is on the bundling and unbundling of property rights to reduce externalities: "[T]he creation of 'new' rights and rebundling of existing rights are really manifestations of the same underlying process…. In all these cases, the driving objective is to internalize externalities subject to the costs of setting up and maintaining the rights… [One strategy is to place] all the interactions within a single module, where presumably they could be dealt with more cheaply." What Langlois labels "externalities" or "interactions," we call "transfers" that generate causal "dependencies" in a T&T network. Thus "internalizing externalities" is equivalent to "encapsulating blocks of transfers." We have arrived at the same place by somewhat different routes.

called "transaction-free zones." Transactions— standardized, counted, and compensated transfers— should be located at the *bottlenecks* of the T&T network. By bottlenecks we mean the points where the information overlap between subnetworks is minimal, for example the completed-pot-hook transfer point in Figure 1. Transfer bottlenecks are the preferred places to locate transactional *gateways* in a T&T network, just as highway bottlenecks are the preferred places to locate toll gates in a road network. At such points, the material, energy, and information transfers are relatively easy to standardize, count, and value, hence the "mundane" costs of converting transfers into transactions will be relatively low.

However, a real T&T network does not consist entirely of blocks and bottlenecks. Many intermediate structures are possible too, and thus the "best place" to locate a transaction is not always as obvious as in the case of the smiths and the cooks. Complicating matters further, the T&T network can be modified within limits. Often it can be "pinched" at particular points in order to create bottlenecks. Such bottlenecks can then serve as narrow gateways, supporting a maximum division of cognitive labor, hence cost-effective transactions. At the same time, transactions can be designed to suit the particular structure of the underlying T&T network. Indeed *relational contracts*, a specialized form of transaction, are especially useful in mediating the difficulties caused by imperfect bottlenecks and overlapping blocks. In the next section, we will describe how a local T&T network and a transaction can be codesigned to be mutually supportive.

"Pinching" the T&T Network

A particular transaction between an engineering plastics company and an automobile manufacturer serves to illustrate how a local T&T network may be "pinched" to create a transfer bottleneck and a transactional gateway between two encapsulated enterprises. The example also shows how relational contracts make cost-effective transactions possible even when the underlying local T&T subnetworks are somewhat overlapping and interdependent. Finally, the example shows how even one degree of ambiguity in the standardized description of a product can dramatically increase the number of transfers of material and information that must take place between a producer and a user in order to successfully complete a transaction.

In 1994, an automobile manufacturer sought to find a new engineering plastic with high heat resistance for automobile interiors. The producer's tasks included specifying an appropriate compound and developing a cost-effective process for making it. One of the authors of this paper (Clark) studied this transaction, and recorded how the automobile company (the user) managed its subcontracting relationship with the engineering plastics company (the producer):

> [T]he automotive customer developed "specifications" that the new material had to meet in order to qualify for and win the business. There were eight items in the specification, including heat resistance, cost, strength and so forth. Each specification was accompanied by a testing protocol and a standard that the material had to meet.[44]

However, it turned out that there were dimensions of performance that were not encompassed by the initial specifications. Hence the standards and accompanying tests were incomplete:

> [A]s development proceeded, it became clear ... that there were other characteristics of the material that were very important to important players in the auto company, which were not in the specs. (Example: the interior designers wanted a material with a "rich, lustrous appearance.") They were not in the specs, because the auto company had no way to make the requirement specific, no testing protocol and no standard to use in the specifications.
>
> The only way to uncover these critical but unspecified parameters was [for the engineering plastics firm] to work closely with the customer and develop material for the customer to test. Success in this kind of development situation... rested on the [engineering plastics] firm's ability to ... understand what the [auto] designers meant by "rich and lustrous," and translate that understanding into technical terms that polymer chemists and chemical engineers could work with, and to move quickly to generate test quantities of material over and over again.[45]

An important criterion left out of the original specs was "rich, lustrous appearance." This was an ambiguous criterion, for the auto designers could not describe it objectively *a priori*, nor could they specify a test for the quality. Because it was ambiguous, the criterion created interdependencies and cycling across the boundaries of the two firms. Many batches of material were formulated, shipped to the auto company, evaluated, and rejected before the compound passed muster on this dimension.

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[44] Clark (1995).

[45] ibid.

Figures 2 and 3 below use task structure matrices to show how the negotiation of a formal contract affected the underlying T&T network. Figure 2 is a schematic diagram of the "raw" or "natural" transfers of material, energy and information between the plastic compound and automobile designs. Figure 3 shows how these natural interdependencies were captured and codified, albeit imperfectly, in a set of eight standards.

The "raw" dependencies between a new engineering plastic and a newly designed automobile were numerous and flowed both ways in the T&T network. That is, the material properties (e.g. weight, viscosity, shapes), the energetic properties (e.g., shock absoption or brittleness) and the informational properties of the plastic (e.g. color, texture) would affect the automobile at each point where the plastic was used. Hence the properties of the plastic would constrain the design of both the automobile and its production process. But those same material, energetic and informational properties would affect the ease of finding the right chemical compound and the cost of making it. Hence, we should imagine the potential task structure matrix prior to the negotiation as (1) having two dense blocks of **x**s representing transfers within the two encapsulated enterprises; but also (2) having many **x**s sprinkled throughout the two off-diagonal blocks. (See Figure 2.)

The out-of-block **x**s indicate that there was an *ex ante* need for many transfers of material, energy and information to occur across the boundaries of the two companies. The sheer number of transfers involved made it problematic to count and arrange compensation for each one. Moreover, to the extent that there were choices to be made about the design of the plastic or the auto, each point of dependency contained a potential conflict of interest. The better choices from the auto company's perspective were likely to be worse from the plastic company's point of view. These inherent conflicts of interest meant that each transfer of material, energy or information between the two companies had the potential to turn into a lengthy and costly negotiation.

Figure 2
The "Natural" or "Raw" Task Structure Matrix Prior to Negotiation

	Engineering Plastics Company														Auto Company										
Engineering Plastics Product and Process Design	.	x	x	x		x	x						x	x											
	x	.		x	x			x		x	x		x	x	x				x						
	x	x	.	x		x			x	x			x	x			x					x			
	x	x	x	.	x		x			x	x		x	x						x					
		x	x	x	.	x			x		x			x								x			
	x	x			x	.			x		x		x	x		x									
	x		x			x	.	x	x		x		x				x								
		x		x		x	x	.	x	x	x			x											
		x			x		x		.	x				x							x		x		
		x					x	x	x	.	x	x		x			x								
			x	x	x	x		x	x	x	.	x													
	x							x		x	x	.		x											
	x						x	x	x		x	x	.			x			x			x		x	
	x				x		x	x		x	x	x													
Automotive Company Product and Process Design				x											.	x		x			x			x	x
													x		x	.		x	x		x	x	x	x	x
		x			x				x						x	x	.	x		x	x	x	x	x	x
			x										x		x	x		.		x	x	x	x	x	x
															x	x		x	.	x	x	x		x	x
			x							x			x		x	x		x		.	x	x	x	x	x
						x									x	x		x	x	x	.	x	x	x	x
								x					x		x	x		x	x	x	x	.	x	x	x
			x		x						x				x	x		x		x	x	x	.	x	x
															x					x		x	x	.	x

There are, of course, many ways to manage in these circumstances. One approach would be to "de-encapsulate" the two firms. For example, the auto company might acquire the engineering plastics company, or the two companies might form a joint venture. Either of these actions would have the effect of creating a larger "transactions-free zone" wherein transfers could take place without needing to be counted, standardized or compensated.

Another approach would be to create one or more proxy measures that were easily counted and standardized, and use those as the basis for a transaction. For example, the auto company might agree to pay the engineering company for "time and materials," as in a standard cost-plus or consulting arrangement. The incentive problems inherent in such arrangements are well known.[46] Nevertheless, when interdependencies threaten to impose overwhelming transactions costs, but de-encapsulation is not an attractive option, cost-plus or consulting contracts may be the next best alternative.

The auto company and the engineering plastics company chose to do something else, however. *They changed the structure of the original T&T network by engaging in an* ex ante *negotiation aimed at standardizing the object that would be transferred.* Figure 3 shows the task structure matrix corresponding to the new T&T network they created. This matrix has three big blocks, instead of two, corresponding to the tasks and transfers of: (1) the initial negotiation; (2) the design and production of the compound by the engineering plastics firm; and (3) the design and production of the automobile using the plastic compound. These blocks are not drawn to scale: in reality the design and production blocks were much larger, that is, involved many more tasks, transfers and agents, than the negotiations block.

Prior to the negotiation, there had to be a sense at both companies that their underlying information sets were substantially non-overlapping, and could remain so. Each group of agents felt they would not have to learn everything about the other's business in order to arrive at a useful and cost-effective plastic compound. Thus there was *ex ante* reason to believe that a transaction between the two companies could be structured at a reasonable cost and with a sufficiently high probability of success to make the uncompensated joint effort of negotiation worthwhile.

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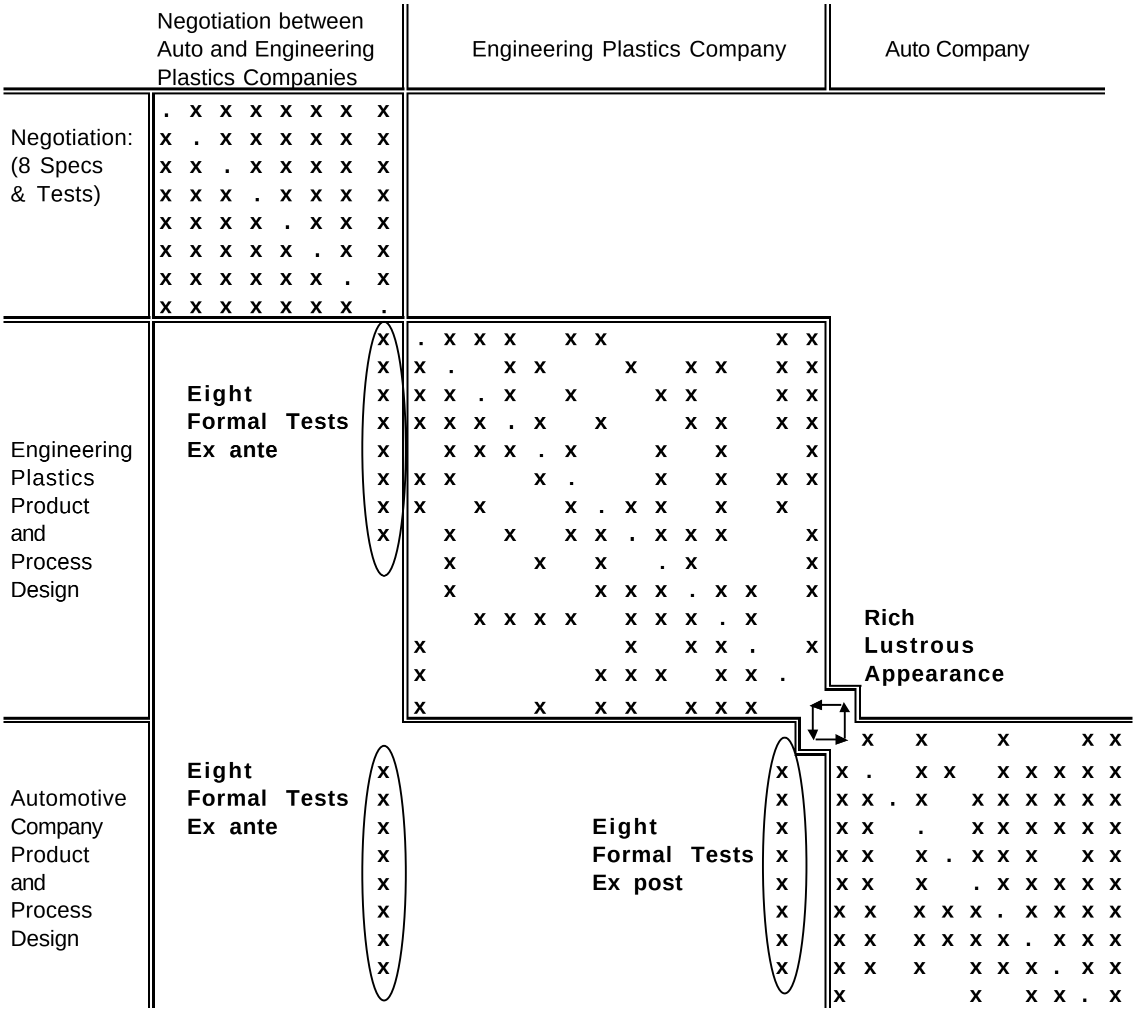
[46] See, among others, Kerr (1975); Shapiro and Stiglitz (1984); Holmstrom and Milgrom (1991); Baker (2000), Baker, Gibbons and Murphy (2002).

Figure 3
A Task Structure Matrix for a Subcontracting Relationship



In the negotiations phase of this transaction, the agents of the two companies had to use their respective information sets to *predict and resolve* the natural interdependencies, shown in Figure 2, between the plastic's and the automobile's design. As it happened, most of the dependencies could be codified in terms of eight criteria that were measurable. The eight specifications and accompanying tests standardized the object of exchange. The standards in turn gave the two parties a common definition of the product and an unambiguous way of determining when the job was done. In effect, the standards partitioned the very large space of possible plastic compounds into two disjoint sets: those that passed the tests and those that did not. And because the standards were codified in terms of testing protocols, it is likely that they were verifiable by a third party in the event of a dispute. But then a dispute was itself less likely in the presence of unambigous standards.

The task structure matrix of Figure 3 shows the effect of standardization on the T&T networks of the two firms after the negotiations. The highly interdependent, information-transfer-intensive negotiations block had as its output an intermediate information good: the eight standards and their tests. Those standards and related tests were then communicated to agents at both firms. In Figure 3, this transfer of design information is denoted by the two sets of **x**s labeled "Eight Formal Tests Ex Ante." Once the contract was signed, those standards became inputs to both the engineering plastics and the automobile design efforts. The standards were also applied as tests when the completed plastic compound was transferred from the plastics company to the auto company: this is denoted by the set of **x**s labeled "Eight Formal Tests Ex Post." In effect, the standards defined an eight-dimensional transactional gateway: the finished product had to pass through this gateway before a transfer of material from the plastics company to the auto company could be counted as a shipment of product and paid for.

The standards resolved *ex ante* a large number of questions regarding what constituted an acceptable product. Because these questions had been resolved, the *ex post* need for ongoing interactions between the two enterprises was reduced dramatically. This is indicated by the absense of **x**s in the off-diagonal blocks between the two encapsulated enterprises in Figure 3. At the same time, transfers within the encapsulated blocks remained as densely interdependent as before.

Thus, through the prior negotition and codification of standards, a very complex T&T subnetwork, spanning the design and manufacture of the engineering plastic compound was "hidden" behind a small number of defined standards and accompanying tests. Such *information hiding* supported an ongoing "division of cognitive labor" between two encapsulated enterprises. Like the smiths and the cooks discussed above, the employees of the automobile company did not need to learn how to design or produce the plastic, and the employees of the plastics company did not need to learn how to design or build an automobile. But whereas the smiths and the cooks could take their common defintion of a pot hook from tradition and convention, the agents of the plastics company and the auto company *had to construct their own common definition of the object* —the compound—that could serve as the basis of their transaction.[47]

Standardizing the product definition in this way involved work for both sets of the agents. The negotiations added costly tasks and transfers of information to the original T&T network. These costs and the costs of applying the standards were *mundane transactions costs*. However, the distillation of interdependencies into eight standards, and the partitioning of the eight dimensional space into "acceptable" and "unacceptable" regions with pre-established, verifiable tests also reduced contractual ambiguity ("Is the product really what we said we wanted to buy?").

Contractual ambiguity is a well-known cause of both mundane and opportunistic *ex post* transaction costs. Indeed, the judicial systems of all advanced market economies are filled with disputes over transactions and contracts that have failed because the standards established before the event were incomplete or ambiguous.[48] Clarity and parsimony in *ex ante* standards generally reduces the *ex post* costs of resolving an arm's length contractual agreement. Thus in this instance as in many others, mundane transactions costs were incurred both *ex ante* and *ex post*, in order to reduce the number and complexity of ongoing transfers between two enterprises as well as the potential costs of subsequent disagreements, disputes and litigation.

Nevertheless a certain amount of indeterminacy can be tolerated in the context of an ongoing commercial relationship, or "relational contract." In this case, there were several

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[47] Information hiding, which is also called "information encapsulation," is a central goal in the design of modular systems. In addition to Parnas (1972a,b) and Parnas, Clements and Weiss (1985), see, for example, Mead and Conway (1980); Ulrich (1995); Gamma et. al. (1995); Baldwin and Clark (1997, 2000); Kernighan and Pike (1999); Salzer (2001); and Langlois (2002). In the economics literature, Cremer (1980), Aoki (1999, 2001) and Aoki and Takizawa (2002) analyze information encapsulation in the context of a general production function subject to stochastic shocks, and have derived the conditions wherein such encapsulation is optimal. To avoid confusion, however, we reiterate the point made above: information transfers are one type, but not the only type, of transfer that gets encapsulated in an encapsulated local system. Material and energy transfers get encapsulated, too. Indeed, material objects and energy are usually more stringently contained within the local system than is information.

[48] Ambiguous contracts are legally unenforceable. Most transaction-cost and contract theory models begin with the premise that some contracts are unavoidably ambiguous, hence unenforeceable, and proceed to analyze the consequences of this fact. See, among others, Williamson (1985); Grossman and Hart (1986); Hart and Moore (1990); Holmstrom and Milgrom (1994); Baker, Gibbons and Murphy (2002).

dimensions of performance that were left out of the initial contract, and only discovered after the fact. One of these dimensions, "rich, lustrous appearance," was highly ambiguous. The ambiguous dimension in turn resulted in a multitude of transfers of material, energy and information back and forth between the two companies. In Figure 3, these transfers, *which were neither counted nor paid for*, are shown as a circuit of arrows between the two enterprises.

In effect, in order to resolve the questions surrounding "rich, lustrous appearance," the two enterprises had to become locally and temporarily de-encapsulated with respect to this issue. That is, agents at each enterprise had to allow a whole set of material, energy and information transfers to occur across their boundaries, which were uncounted, unstandardized and uncompensated. In allowing such transfers, each enterprise risked being overburdened and undercompensated by the other. But, because there was trust (mutual reputation) and the expectation of a continuing commercial relationship on both sides of the contract, a small "transactions-free zone" could be sustained in the context of the commercial relationship. That zone, in turn, was used to resolve the issue of "rich, lustrous appearance" to the satisfaction of both parties. In practice, some ambiguity, hence interdependency and risk of opportunism was expected and tolerated within the framework of the relational contract.[49]

Modularity and Mundane Transaction Costs

A complex system is said to exhibit *modularity* if its parts operate independently, but still support the functioning of the whole. Modularity is not an absolute quality, however. Even within the same class, systems can exhibit different modular architectures and different degrees of interdependence between their respective elements.[50]

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[49] Baker, Gibbons, and Murphy (2002) show, generally, that relational contracts elicit more performance effort than corresponding spot contracts. However, they do not consider potential linkages between *ex ante* contractual ambiguity and the *ex post* effort needed to complete a transaction successfully. Still, if ambiguity can be resolved with effort, it is not surprising that relational contracts can support more ambiguous contract terms than spot contracts.

[50] This definition is taken from Rumelhart and McClelland (1995), as quoted in Baldwin and Clark (2000). Although Herbert Simon did not use the term "modularity," the attribute we now call by that name is essentially identical to the property he called "near-decomposability." This can be seen by referring to the matrix maps of modular and near-decomposable systems. (Simon, 1999; Simon and Augier, 2002.) On the

In the T&T network, a module is a group of tasks and transfers that are densely connected within the group, but only loosely connected to the other parts of the network.[51] In a TSM mapping, modules appear as densely connected blocks. If there are only a few, simple out-of-block transfers, then the underlying network is highly modular. As the number and complexity of out-of-block transfers increases, the modularity of the network decreases.

Sometimes the modular structure of a particular T&T network is highly constrained by the laws of physics and logic, hence very inflexible. The smiths-and-cooks network is an example of such an inflexible modular structure. Material, energy and information transfers within the smithy and the kitchen needed to be dense and complex (see above). But, as we saw, between the smithy and the kitchen, there was a "natural" transfer bottleneck that supported an almost complete division of cognitive labor.[52]

In other cases, however, the laws of nature afford the designers of a T&T network more latitude. In the engineering plastic example, there were at least three possible T&T alternatives: (1) the "natural" interdependent structure depicted in Figure 2; (2) the "proto-modular" structure shown in Figure 3; and (3) a "fully modular" structure, which would have eliminated the interdependencies and cycling caused by the "rich lustrous appearance" issue. The designers of the engineering plastic contract implicitly chose among these three alternatives. They simultaneously selected a proto-modular structure for the T&T network and matched it with a negotiated, relational form of transaction. They also chose what to contract on: a compound that conformed to eight standards plus some to-be-specified criteria, instead of time-and-materials or a compound that conformed to the eight standards only.

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economic properties of modular systems, see, among others, Langlois and Robertson (1992); Baldwin and Clark (1992, 2000); Ulrich (1995); Garud and Kumaraswamy (1995), Sanchez and Mahoney (1996); Schilling (2000); Aoki (2001); Langlois (2002); Aoki and Takizawa (2002); Garud et. al. (2002) and the papers therein.

[51] This is known as the "small worlds" property of a network (Watts, 1999). Small world networks are perforce systems with a high degree of modularity.

[52] As should be evident, an "inflexible modular structure" means that graph structure of the network is relatively fixed. A system of production with an inflexible modular structure may operate very flexibly by, for example, mixing and matching the outputs of the blocks.

In choosing the degree of modularity for the T&T network plus the object and form of the transaction, the contract designers traded off economic costs and benefits on a number of dimensions:

- the quality of the final compound;
- the costs of *ongoing transfers* between the two enterprises in the course of doing the work;
- the *mundane transaction costs* of standardizing the object, counting its quality (as well as quantity), and paying for what was delivered; and
- the opportunistic transaction costs of holdup, shirking, defensive investment, reneging and *ex post* disputes.

The second and third items on this list, i.e. ongoing transfers vs. mundane transaction costs are respectively the benefits and costs of a *modularization*.

A modularization "pinches" the T&T network at a particular point (or points), by reducing the dependencies that cause transfers of material, energy and information while work is going on. The process of modularization in turn is the process of (1) defining modules; and (2) eliminating dependencies between modules. In any modularization, one must create a set of specifications for each module (what the module will do, how it will interact with other parts of the system) and related tests (is the module acceptable, does it work within the system, how well does it work). Taken together, the specifications and tests are known as the *design rules* of the modular system.[53]

If the modularization is "good enough," the design rules will address and resolve essentially all the latent interdependencies between the individual modules. In that case, as long as the design rules are obeyed, work on the individual modules can proceed independently. When the work is done, the modules can be linked together, and they will function together as a system.

By definition, then, a modularization partitions an erstwhile interconnected network into discrete subnetworks, called modules, which can function together because they jointly recognize and obey a set of design rules. Thus when a particular T&T network is modularized, necessarily,

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[53] Baldwin and Clark (2000), Chapter 3. Note that in traditional and "low-tech" systems of production, the design rules supporting modular systems may be expressed in vernacular language and known to everyone. For example, the names and definitions of common iron implements used in a kitchen are in effect the design rules linking a smithy and a kitchen.

new transfer bottlenecks are created. These in turn can serve as cost-effective transactional gateways. In the new modular network, gateways will exist:

- between the design rules and each module;
- between "upstream" modules and "downstream" modules, as in a supply chain; and possibly,
- between "upstream" modules and "downstream" systems integrators.

Of necessity, these new gateways will have relatively low mundane transaction costs relative to transfer points within the modules. By creating gateways, therefore, a modularization creates the possibility for cost-effective transactions to occur, where no such possibilities existed before.

Conclusion

We can now answer the question we posed at the beginning of this paper. Where do transactions come from? Why do transactions arise where they do? Our answer to the first question is: transactions come from the modular structure of an underlying network of tasks and transfers of material, energy and information. By construction, transfers *within* modules in this network are numerous and complex, while transfers *between* modules are relatively few and simple. Thus the between-module transfer points constitute a set of "gateways" in the network. These are places where the division of cognitive labor is greatest, and the mundane costs of setting up transactions are lowest. Cost-effective transactions may be located at these gateways.

The costs of setting up a transaction at a particular transfer point in a T&T network are the costs of standardizing the object being transferred, counting it, valuing it, and paying for it. In a modular system, a standardized description of each module and tests of its conformance with the rest of the system must exist as part of the system's design rules. Thus it is not surprising that between-module transfer points are also least-cost locations for transactions. In effect, at those points, standardization, which is a critical part of the work of creating a transaction, has already been done as part of the engineering design of the system.

But why do transactions arise at all? What good are they? Why have them? We note that if a transfer has already been standardized, then the remaining work needed to convert that transfer into a transaction is the work of counting the individual transfers, valuing them, and paying for them. In a large, complex system, counting transfers between encapsulated local units serves as decentralized control mechanism for regulating flows between the units. At the same time, providing reciprocal compensation serves as both a control mechanism and a lateral coordinating signal.

In principle, with decentralized control and lateral coordination mechanisms in place, an entire system can coordinate flows of material, energy and information and still maintain an overall resource balance *without central control*. Thus the combination of (1) modularity in the design of tasks and transfers; (2) encapsulated local systems serving as transaction-free zones; and (3) transactions serving as signals and maintaining an overall balance, may allow a very large T&T network to operate in a distributed and robustly decentralized way.

What's more, in that network, local experiments can be used to try out new products and new production processes within the context of a (relatively) stable larger system. In this fashion, the network itself can evolve piecemeal, with most innovations causing only local disruptions in the overall system. From an engineering perspective, this is indeed a remarkable design.

Appendix: The Effects of Encapsulation

Transactional encapsulation is a complex social technology and set of procedures. The technology and procedures have changed, generally becoming more efficient over time. They have also diffused across cultures. Some technologies and some procedures have been codified in the laws of sovereign states, for example the laws governing incorporation and conferring limited liability on corporations.[54] Other technologies and procedures, such as double-entry book-keeping,[55] the functional design of an enterprise,[56] and the design of financial claims and payment systems,[57] fall under the aegis of the theory and practice of management. (The history of encapsulating mechanisms is indeed fascinating, but would take us far beyond the scope of this paper.)

It is notable, however, that all complex systems appear to need encapsulating mechanisms.[58] Indeed, biological systems exhibit encapsulation at various levels, for example, the nucleus, which contains genetic material, is an encapsulated subsystem within a cell; cells are encapsulated within cell walls; within multi-celled organisms, the germ-line is encapsulated in the reproductive organs; organisms also have encapsulated bodies; and social insects, such as ants and termites, build encapsulated nests.[59]

In biological and economic systems, encapsulation appears to have two main effects. First, encapsulation protects material, energy and information transfers inside the capsule from being disturbed by outside interference. Second, encapsulation permits the storage of material, energy and information inside the capsule over time. In this fashion, encapsulation allows stable

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[54] Moss (2002); North (1990).

[55] Crosby (1997); Favier (1998).

[56] Chandler (1977); Koehn (2001).

[57] Merton and Bodie (1995, 2002).

[58] Although he did not use the term "encapsulation," Herbert Simon emphasized the need to separate the "inner" system of a goal-directed structure from the "outer" environment: "It is an important property of most good designs, whether biological or artifactual… [that] the designer insulates the inner system from the environment, so that an invariant relation is maintained between the inner system and goal, independent of variations …[in] the outer environment. … Quasi-independence from the outer environment may be maintained by various forms of passive insulation, by reactive negative feedback…, by predictive adaptation, or by various combinations of these." (Simon, 1999, p. 8.) In other words, encapsulation is essential, but it can be achieved in many different ways.

[59] Maynard Smith and Szathmary (1995); Gerhart and Kirschner (1997); Turner (2000).

local systems, involving complex material, energy, and information transfers and temporary imbalances of material and energy flows, to exist.[60]

In biological systems, encapsulated local systems like single and multi-celled organisms can compete with their unencapsulated surroundings *and with each other* for scarce resources. Importantly, in some cases, encapsulated local systems can also cooperate and perform specialized complementary functions. Such cooperation gives rise to the internal structure of the cell, multicellular organisms, and social species, like ants. The most successful singletons and groups will survive, either physically or, more commonly, as information patterns and structures (for example, through the biochemical processes of living cells or the replication of genes).[61]

The surviving local systems, in turn, can sometimes (but not always) be incrementally modified, especially if their internal structure is *modular*.[62] Thus, in addition to enabling stable local systems to form, encapsulation gives rise to two new "levels of selection" in a biological system: the capsules and, possibly, groups of complementary capsules. The emergence of these new levels of selection in turn changes the evolutionary or adaptive trajectories that are open to the larger system. *This change in evolutionary potential is the third effect of encapsulation.* It is important to note, however, that the ability to survive and the ability to evolve are not the same thing. If encapsulation promotes the survival of a local system, then the phenomenon of encapsulation may persist, even if the particular encapsulated local systems do not evolve.[63]

In an economy, transactionally encapsulated local systems include individuals, families, and corporations. With respect to the T&T network, transactional encapsulation has many of the same effects that physical and chemical encapsulation has in biological systems. It can be used to isolate "fragile" parts of the T&T network from external shocks.[64] It allows not only specific

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[60] Maynard Smith and Szathmary (1995); Gerhart and Kirschner (1997);

[61] Gerhart and Kirschner (1997); Haig (1997); Margulis (1970, 1981); Turner (2000).

[62] Note that modularity requires at least two levels of hierarchical structure: the system and the modules. Each level will require encapsulating mechanisms, hence there will be two levels of encapsulation.

[63] Gerhart and Kirschner (1997).

[64] On the disruptiveness of external shocks, like the phone ringing at the wrong time, see Herbert Simon's famous parable of the two watchmakers (Simon, 1999, pp. 188-190). Of course, the hapless Tempus, whose watches fell apart when he answered the phone, might have protected his fragile system of production by setting up a voicemail account or hiring a receptionist. Thus, if Tempus had set up an encapsulated local system with slightly different boundaries, he might have been able to compete with Hora's more modular and robust system of production.

materials but also general claims (money and credit) to be stored within a local system, e.g., a family or a corporation. Those stored resources in turn can be used to adjust for temporary imbalances within the local system and between the local system and the larger system. Finally, transactionally encapsulated local systems can compete *as units* for material, energy, human and financial resources. Those individual capsules and groups that are most successful in securing and storing resources will survive, perhaps indefinitely. And those that can be modified at low cost may evolve in response to competitive selection pressures.

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