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Knowledge, consumption, and endogenous growth*

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Abstract. In neoclassical theory, knowledge generates increasing returns – and therefore growth – because it is a public good that can be costlessly reused once created. In fact, however, much knowledge in the economy is actually tacit and not easily transmitted –and thus not an obvious source of increasing returns. Several writers have responded to this alarming circumstances by affirming hopefully that knowledge today is increasingly codified, general, and abstract – and increasingly less tacit. This paper disputes such a trend. But all is not lost: for knowledge does not have to be codified to be reused and therefore to generate economic growth.

Key words: Tacit knowledge – Increasing returns – Growth theory – Knowledge reuse – Codification

JEL-classification: O3, O4

1 Introduction

The recent efflorescence of interest in "endogenous" theories of economic growth has focused attention on the nature and role of knowledge in the growth process (Romer, 1986, 1990; Grossman and Helpman, 1990, 1994). Unlike earlier models of growth (Solow, 1956; Swan, 1956) in which technological change appeared as an exogenous parameter, this New Growth Theory (NGT) has sought to "endogenize" technical change by folding its production more fully into the

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neoclassical positive heuristic. Knowledge no longer appears as manna from heaven, but is now produced just as are bananas and tires: as the result of the rational optimizing behavior of economic agents.[1] These agents invest resources in Research and Development (R&D), a sausage machine whose output is new technological knowledge. For reasons that Kenneth Arrow (1962) long ago articulated, however, the good called knowledge has certain peculiar properties in that, once created, it can spill easily into the hands of others at zero marginal cost.[2] This process of spillover (and the nonconvexity it implies) is the source of the increasing returns that generate economic growth.

While not questioning some essential truth to this story, students of the process of technological change – especially those who have not restricted themselves to theoretical models – have expressed considerable doubt about the this picture of technological knowledge and its creation. Those who study the historical processes of technical change have found that knowledge does not always – and perhaps does not usually – take the form Arrow assumed (Nelson, 1992). Much technological knowledge cannot in fact be transmitted easily to others; much technological knowledge is inarticulate and tacit (Polanyi, 1958), and can be transmitted only at a cost through imitation and apprenticeship. This observation creates a difficulty for knowledge-based theories of growth. To the extent that knowledge is tacit in this way, it behaves like an ordinary private good, and its role in generating increasing returns is lost.

One response to the problem of tacit knowledge among sophisticated students of innovation has been to create a clear distinction between knowledge that is tacit and knowledge that is *codified*. Codified knowledge is knowledge that has been (or can be) converted into symbols for easy transmission, replication, and storage (Boisot, 1995; Saviotti, 1998). Such knowledge thus partakes of Arrovian public-good properties, which makes it a potential source of increasing returns. Under this stratagem, the large place of tacit knowledge in social learning does not invalidate growth theory so long as there also exists codified knowledge in suitable quantities. Some writers would even go further, suggesting that technological change and economic growth have had the effect of tipping the balance between tacit and codified knowledge (Arora and Gambardella, 1994; Cowan and Foray, 1997). "More" knowledge is becoming codified, implying (and perhaps explaining) an accelerated pace of social learning and economic growth.

This essay takes a more skeptical view of the proposition that we are experiencing greater codification hand in hand with modern technology and economic growth. But such skepticism need not have dire implications for (the theory of) economic growth. The essay will take an equally skeptical view of the proposition that only codified knowledge, and never tacit knowledge, can generate economic growth.

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[1] It thus strikes me as somewhat incongruous that proponents of the New Growth Theory refer to the older Solow-Swan approach as "Neoclassical" Growth Theory, implying that the NGT is somehow not neoclassical. By the accepted criteria of the philosophy of science, it is the other way around. For a more general critique of the NGT see Langlois and Robertson (1996).

[2] To be precise, knowledge is nonrival and (only) partially excludable (Romer, 1990, p. S74).

2 Knowledge as structure

Part of the difficulty in understanding the economics of knowledge is that the literature is filled with cross-cutting and often mutually inconsistent distinctions and definitions: tacit versus explicit or codified knowledge; general versus localized knowledge; abstract versus concrete knowledge – and even the hoary distinction between knowledge and information. This essay may not sort out these tangles, and may even make matters worse. But it is arguably useful to begin with some attention to what one means by knowledge.

Knowledge is a peculiar commodity in ways that go well beyond its (sometime) public-good character. At base, knowledge is always *structure*. It is therefore an inherently qualitative concept. Kenneth Boulding put it this way.

> [W]e cannot regard knowledge as simply the accumulation of information in a stockpile, even though all messages that are received by the brain may leave some sort of deposit there. Knowledge must itself be regarded as a structure, a very complex and frequently quite loose pattern, ... with its parts connected in various ways by ties of varying degrees of strength. Messages are continually shot into this structure; some of them pass right through its interstices ... without effecting any perceptible change in it. Sometimes messages "stick" to the structure and become part of it. ... Occasionally, however, a message which is inconsistent with the basic pattern of the mental structure, but which is of a nature that it cannot be disbelieved hits the structure, which is then forced to undergo a complete reorganization. (Boulding, 1955, pp. 103-104, quoted in Machlup, 1983, p. 643n).

The association of knowledge with structure is intuitively appealing, if still rather vague. What makes a structure "knowledge"? At some level, a structure constitutes knowledge if that structure is ordered in a way that produces results. Think of genetics. We can say that DNA is a knowledge structure because it is an orderly arrangement that "knows how" to do something, namely how, in conjunction with an existing organism, to generate a new organism. That new organism in turn is also an ordered structure that does something, namely survive the evolutionary process.

Donald MacKay thinks of a system's structure as defining "conditional states of readiness" on which a signal operates. It is the overall configuration that determines the meaning – and the meaningfulness – of a message. "It isn't until we consider the range of other states of readiness, that *might have been considered but weren't*, that the notion of meaning comes into its own. A change in meaning implies a different selection from the range of states of readiness. A meaningless message is one that makes no selection from the range. An ambiguous message is one that could make more than one selection" (MacKay, 1969, p. 24, emphasis original). MacKay offers the metaphor of a railroad switching yard in which the configuration of tracks and switches stands ready to direct the trains passing through it. By sending the right electronic signal (or, in older yards, by inserting the correct key in a switch-box) one can rearrange the configuration of tracks. The meaningfulness of a message thus depends on its form – on the shape of the key. And that meaning consists in the change the message effects in the arrangement of the yard, the selection it makes from the set of all possible configurations.

But where does the structure of knowledge – the railroad switching yard – come from? How does it form, and how is it modified by experience? As recent work in cognitive science is suggesting (Holland et al., 1986; Edelman, 1992), human learning involves the building up of a structure of categories (of conditional states of readiness) from experience. Through a rule-guided process of sorting, new experiences are shunted into appropriate categories, and these experiences may at the same time help reinforce or change the structure. As F.A. Hayek long ago put it, "that which we call knowledge is primarily a system of rules of action assisted and modified by rules indicating equivalences or differences of various combinations of stimuli"[3] (Hayek, 1978, p. 41). To study the growth of knowledge is thus to study the evolution of systems of rules of action.

A conceptualization of knowledge as involving rule-following systems is certainly consistent with the general understanding of tacit knowledge. Nelson and Winter (1982) have associated Polanyi's concept with the notion of *routines*, which they see as the basic element of human action. Routines are habitual patterns of behavior that embody skill-like knowledge.[4] Such knowledge cannot be articulated or transmitted explicitly but must be acquired over time through a process of apprenticeship and trial-and-error learning. A structure of routines – in an individual, an organization, or a wider institution – is clearly a system of rules of action and a knowledge structure (Langlois, 1997).

But what about codified knowledge? As Kenneth Arrow (1974, chapter 2) notes, individuals and organizations can have a particular kind of knowledge structure that is able to understand information consisting of explicit symbols. In the first instance, these symbolic transmissions are *information* not knowledge. They are codes that activate the rule-based categorization system of the receptor structure in a meaningful way. It is the structure, not the signal, that is knowledge; and, in general, the knowledge structure is not itself codified in an important way and may be mostly tacit.[5] Even though Chinese characters can be beautifully

[3] Hayek's *Sensory Order* (1952) arguably anticipated what is the dominant direction of thought among cognitive theorists today (Weimer, 1982; Edelman, 1987).

[4] Cowan and Foray (1997), however, attempt to connect routines to codified knowledge. In some cases, they write, "a procedure that was developed to produce some end becomes routinized, and repeatable, which implies that it can be broken down into component pieces, each of which is sufficiently simple that it can be described verbally, or embodied in a machine. This, again, is a process in which tacit knowledge becomes codified." Although repetition and routine may certainly lead to embodiment in machines (a point to which I return below), I do not see such embodiment as necessarily a process of codification. Nor is it obvious that repetition and replicability by themeselves lead to codification. A slam dunk is (broadly) repetitive and replicable, but no one can write a code that would fairly describe it let alone allow anyone to replicate it who had not also engaged in a lengthy process of learning-by-doing.

[5] Recently, Cowan, David, and Foray (1999) have attacked the too-ready use of the term "tacit knowledge" in economics and policy circles, and have attempted to provide a taxonomy of types of knowledge. In their view, knowledge is either already codified or not codified. Knowledge that

written in pen and ink, the knowledge structure necessary to read the characters has to have been built up by years of skill training.

Some writers, including Cowan and Foray (1997), seem to be making a larger claim, namely, that *knowledge* is increasingly becoming codified. The sense of the term "codified knowledge" must be that *some of the structure itself* is transformed into coded messages, which can then be decoded by others and turned back into structure.[6] For example, I could transform my tacit knowledge of Chinese (if I had any) into the symbols on the page of a textbook, which others could read in order to acquire (tacit?) knowledge of the language. Since much of the mechanism of language comprehension and use is inherently ineffable, this kind of translation is notoriously imperfect.[7] So even if we observe more codified *signals* in modern society, it is problematical to say that we have therefore observed more codified *knowledge*. And it is even more problematical to assert that we experience nowadays a greater proportion of codified to tacit knowledge.[8] *Ulysses* contains far more coded symbols than does *Where the Wild Things Are*; but understanding the former (if that is indeed possible) requires a far greater store of tacit knowledge than does understanding the latter.

The allure of codified knowledge stems, I believe, from the perception that codification is related to generality and abstractness. If a bit of information can be codified, that means it can be transcribed in some systematic form. System implies generality, perhaps even an understanding of abstract underlying principles. And here is the important point: knowledge that is general can be applied in many different concrete circumstances, thus spreading overheads widely and creating increasing returns.

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is not codified – and therefore "tacit" – can be uncodified either because no "codebook" has ever been created or because the codebook exists but has been "displaced," that is, the codebook is not explicit but resides in the heads of those who possess the knowledge. These authors also stress, quite rightly, the role of economic incentives in determining how much knowledge gets codified. Although I find this exercise an extremely valuable one, I remain a bit troubled by the authors's (tacit?) assumption that all knowledge is potentially codifiable, at least in principle. In my view, this misses the point of epistemological and phenomenological critics, who would insist – in opposition to some scholars of artificial intelligence in computer science – that knowledge must always retain an irreducible tacit or contextual component (Dreyfus, 1979). For Cowan, David, and Foray, tacit knowledge is just knowledge not codified (but potentially codifiable). For these critics, by contrast, all knowledge is both codifiable *and* (inherently) non-codifiable: *some* parts or aspects of all knowledge can be codified, but some parts can *never* be codified. It is always possible in principle to create a codebook, but that codebook will never capture all the knowledge held by the individuals whose code it is.

[6] There is of course no fine line between transmitting information and transmitting knoweldge, as even information may alter the structure into which it is transmitted. In fact, as Machlup points out, "[a]ny kind of experience – accidental impressions, observations, and even 'inner experience' not induced by stimuli received from the environment – may initiate cognitive processes leading to changes in a person's knowledge. Thus, *new knowledge can be acquired without new information being received*" (Machlup, 1983, p. 644, emphasis original).

[7] Indeed, much of the force of a textbook actually consists not in coded representations of the knowledge sought but in injunctions to go forth and acquire tacit skills – through readings, problem sets, exercises, listening to tapes of native speakers, etc.

[8] A point that Cowan and Foray acknowledge.

Arora and Gambardella (1994) make an argument in the same spirit as that of Cowan and Foray, but one couched not in terms of codification but directly in terms of abstractness and generality.[9] Technological change, they say, once rested largely on localized tacit knowledge gained from trial and error. Increasingly, however, scientists and technologists are able to distill abstract ideas and general principles from their experiments, which they can then apply successfully in other concrete circumstances. It is this (increasing) generality and abstractness that, in effect, gives rise to the R&D sausage machine of endogenous growth theory. Because abstract knowledge can be applied widely, innovation is no longer tied to trial-and-error learning in particular concrete circumstances. And individuals can increasingly *specialize* in the production of new knowledge, thus finally bringing to reality Adam Smith's prediction that innovation would become the business of "philosophers or men of speculation, whose trade it is, not to do any thing, but to observe every thing; and who, upon that account, are often capable of combining together the powers of the most distant and dissimilar objects"[10] (Smith, 1976, I.i.9, p. 21).

Much of this may be true. In my view, however, the literature praising codified, general, and abstract knowledge – and its allegedly increasing importance in modern society – misses three crucial and related points. The first is that generality and abstractness do not require codifiability or explicitness.[11] Those of us who write about capabilities and routines are often prone to phrases like "idiosyncratic and tacit knowledge." But tacit knowledge need not in fact be idiosyncratic. Dasgupta and David (1994, p. 494) are right when they say, "we find no compelling grounds for associating the tacit knowledge of either technologists or scientists necessarily with skills that are specific rather than 'generic' in their applicability." Knowledge of Chinese is surely a tacit skill, but one that reflects highly abstract knowledge with very general applicability. It is also far from idiosyncratic, being shared by something like a billion people.

The second point is that knowledge can be externalized and made less idiosyncratic in ways that do not necessarily involve codification. Knowledge is structure. And knowledge can thus be externalized beyond an individual creator by being imbedded either in machines and other physical technology or in various kinds of social or behavioral structures that I will broadly call institutions.

[9] "By 'abstract' we mean the ability to represent phenomena in terms of a limited number of 'essential' elements, rather than in terms of their 'concrete' features. By 'general' we mean knowledge that relates the outcome of a particular experiment to the outcomes of other, more 'distant' experiments." (Arora and Gambardella, 1994, p. 524.)

[10] Of course, Smith did not view this as a prediction, but saw it as already characteristic of invention in his own day. And he was right. As H. I. Dutton (1984, especially pp. 112-117) has shown in his study of patening during the Industrial Revolution, invention was already becoming a specialized activity in Smith's day, and the process accelerated throughout the nineteenth century. The same was true of the American Industrial Revolution (Lamoreaux and Sokoloff, 1999).

[11] Compare Cowan and Foray (1997): "Typically, a piece of knowledge initially appears as purely tacit–a person has an idea. Often, though, as the new knowledge ages, it goes through a process whereby it becomes more codified. As it is explored, used, and better understood, less of it remains idiosyncratic to a person or few people, and more of it is transformed into some systematic form that can be communicated at low costs."

These latter include imitable routines and skills; organizations; and abstract institutions like law, language, or culture. In discussing the historical sources of American economic growth, Gavin Wright (1999, p. 296) notes that technological knowledge "is not simply a body of abstract information, but is inherently social, embedded in terminology, in procedures, in physical equipment and in products." The nonconvexities that gave rise to growth in the United States arose from the increasingly national character of the "learning networks" that lay behind technological change. In effect, increased economic integration and labor mobility tended to standardize and generalize the country's knowledge-bearing institutions, permitting the knowledge they contained to be more widely reused and to be spread over more concrete applications. (I return to this theme below.)

The third point is that social institutions are often valuable precisely because and to the extent that they *obviate* the codification of knowledge. As Alfred North Whitehead remarked, it is "a profoundly erroneous truism, repeated by all copy-books and by eminent people when they are making speeches, that we should cultivate the habit of thinking what we are doing. The precise opposite is the case. Civilization advances by extending the number of important operations which we can perform without thinking about them"[12] (Whitehead, 1911, p. 61). Or, we might add, without describing them explicitly. To the extent that institutions embody knowledge, they make it less necessary for us to transmit information or acquire knowledge, codified or otherwise. Basketball players can execute such highly complex maneuvers as a fast break with only a minimal set of non-verbal signals. Similarly, professionals working in the same area of technology can often communicate insights and ideas with only minimal sets of signals. Well-functioning teams and organizations can operate effectively with no communication at all. Indeed, in such cases to observe a large amount of codified transmission would be evidence of less-effective knowledge structures – not evidence of "more" knowledge.[13]

3 The reuse of knowledge

An important part of my argument here is that, because knowledge – even, or maybe especially, tacit knowledge – can be imbedded in institutions, we need to look to institutions for the sources of the nonconvexities that give rise to increasing returns and economic growth. That institutions partake of increasing returns is certainly well known (North, 1990, p. 95). But what is the source

[12] As Whitehead adds: "Operations of thought are like cavalry charges in a battle – they are strictly limited in number, they require fresh horses, and must only be made at decisive moments." I am indebted to both Brian Loasby and Bhaven Sampat for directing me to the original source of this quotation.

[13] Cowan and Foray (1997) are right in pointing out that "it is in the context of change that we might find situations of excess codification." When the environment is changing, knowledge structures (whether tacit or codifying) are becoming less well adapted, leading to the generation and transmission of more codified information during the process of readaptation. This phenomenon is related to the "dynamic transaction costs" that can afflict organization in a world of rapid change (Langlois and Robertson, 1995).

of those increasing returns?[14] I have argued elsewhere (Langlois, 1999b) that increasing returns can in most cases be understood as instances of *the reuse of knowledge*.

There are two mechanisms by which the reuse of knowledge can generate increasing returns, and both are driven by the extent of the market. The first is better appreciated: Smith's division-of-labor effect. The second is distinct and less often noticed; it is related to what I have called the "volume effect" (Langlois, 1999a).

In the Smithian story, labor starts out unspecialized, in that each worker performs many different tasks; but each of the many tools the worker uses is specialized to a particular task. The division of labor consists in specializing labor to the same level as the already-specialized tools. This does not exhaust the possibilities, however. It is also possible, through mechanical innovation, for tools to become less specialized – to integrate previously separate tasks as the extent of the market grows (Ames and Rosenberg, 1965; Robertson and Alston, 1992). Transferring these tasks to machine embeds in the machine the knowledge of how to perform the tasks.

> In drilling the plate A without the jig the skilled mechanic must expend *thought* as well as skill in properly locating the holes. The unskilled operator need expend no thought regarding the location of the holes. That part of the mental labor has been done once for all by the tool maker. It appears, therefore, that a*"transfer of thought*" or *intelligence* can also be made from a person to a machine. If the quantity of parts to be made is sufficiently large to justify the expenditure, it is possible to make machines to which all the required skill and thought have been transferred and the machine does not require even an attendant, except to make adjustments. Such machines are known as *full automatic* machines. (Kimball, 1929, p. 26, emphasis original)

As this quote from an old text on the organization of industry suggests, the transfer to a machine of "intelligence" archetypically takes the form of a jig, pattern, or die. And, as Alchian (1959) points out, the "method of production is a function of the volume of output, especially when output is produced from basic dies – *and there are few, if any, methods of production that do not involve 'dies'*" (Alchian, 1959 [1977, p 282], emphasis added). Why? Because, with increased volume, it pays to invest in *more durable* dies.

Consider the example of printing. If one is going to run off a few copies of a memo, a photocopy machine will do the trick. If one needs several hundred copies of documents on an ongoing basis, it might be worth investing in a small offset press. For even larger predictable production runs, it would pay to have a more serious printing press. As volume and predictability allow greater "durability of

[14] North (1990, pp. 94-95) cites four reasons that Brian Arthur (1988) had articulated in the context of technology: large set-up or fixed costs; learning effects; coordination effects; and adaptive expectations. The last three of these have obviously to do with knowledge. I argue below that even the notion of amortizing fixed set-up costs can be understood in terms of the reuse of knowledge.

dies," unit costs decline. This is an effect of growth in the extent of the market distinct from the division of labor narrowly understood. And the reason that costs decline as dies become more durable is not because the knowledge itself leaks out but because the knowledge – created once – is spread over more and more units.

The first mechanism of knowledge reuse – the Smithian division of labor – also operates by imbedding knowledge rather than by transmitting it. But in this case the knowledge is imbedded in organizations and institutions rather than in technology. Smith's own account of the division of labor is very much about how (re)organization can yield increasing returns – about how knowledge can be imbedded in an organizational structure and, through standardization, can both substitute for and amplify the knowledge the individual workers possess (Leijonhufvud, 1986; Langlois, 1999a).

Notice that, in the case of organizations and institutions as in the case of technology, standardization is arguably the fundamental source of increasing returns. Here, however, it is behavior rather than physical technology that is standardized. Whether it is a classical Weberian bureaucracy (Mintzberg 1979) or an association as diffuse as a profession (Savage and Robertson, 1999; Langlois and Savage, 2000), the organization achieves coordination by standardizing the repertoire of routines its members possess. This is just as clearly true in the case of institutions, which, in a fundamental sense, are standards that orient behavior[15] (North, 1990). To take a simple example, the rule that one always drive on the right in the United States is an institution that allows us to coordinate our behavior with that of others by forcing us to reuse the same piece of knowledge over and over.

Perhaps the case of software will illustrate these points. In terms of embedded technology, software is the paradigm case of knowledge reuse through durable dies. Once written, a piece of code can be stamped out an indefinite number of times at little more than the marginal cost of burning a CD (Shapiro and Varian, 1998). The idea of knowledge reuse, however, is generally associated with a somewhat different aspect of software production. Michael Cusumano (1991) argued that vertically integrated Japanese software houses may have advantages over decentralized American ones because the Japanese firms are better able to reuse portions of code written for earlier applications. Unlike American firms, Japanese firms can "remember" and don't have to start each new application from scratch. Notice that the increasing returns here arise in the context of economies of scope rather than of scale.[16] Notice also, however, that the economies arise (a) from standardization and (b) within the context of organization. The function

[15] I am implicitly following North's (1990) distinction between institutions as the abstract rules of the game versus organizations as collective actors operating within the rules. In fact, however, the distinction is far more complex and blurry (Langlois, 1995).

[16] Depending, of course, upon how narrowly one defines the product. Reuse of code gives economies of scope if it reduces the costs of producing different applications, but it gives economies of scale in the production of "more software."

of memory is embedded in the Japanese firms in a way that it is (supposedly) not embedded in the American ones.

It turns out, however, that the "software factory" approach does not seem to have given Japanese firms anything like an advantage against American software developers. Rather the opposite is the case. The reason is that American firms have benefited from two other, more powerful, forms of standardization: standardized hardware platforms and object-oriented programming[17] (Mowery, 1995, p. 310). By reducing variety, the former reduced any economies-of-scope benefits the factory approach may have conveyed. And, by creating public standards, object-orientation pushed the reuse of knowledge from the organizational to the institutional realm, effectively creating *external economies of scope* (Langlois and Robertson, 1995, p. 5).

4 Standardization and variety

Let me recast the argument a different way. Generality – the wide applicability and reusability of knowledge – is a source of increasing returns. But the limits to generality do not come from the tacitness of knowledge, since tacit knowledge can in fact be general. Moreover, all knowledge can be embedded in technology and institutions, and thus can be reused without being replicated *qua* knowledge through the Arrovian mechanism. What limits generality thus comes less from the supply side than from the *demand* side. That is, it is the demand for variety that, by limiting the possibilities for standardization, limits the reuse of knowledge. Bresnahan and Gambardella put it nicely.

> An inherent tension in any division of labor is that the distinct users of a technology, or for that matter of a good or service, employ it for different purposes. Consequently, they have different needs, and these needs would be best satisfied by producing, adapting, or using the technology or input according to their special goals and demands. This is a force for localization. Standardizing the technology or input allows exploitation of the gains from specialization, while localizing it permits superior matching. A general specialty is a compromise between the scale economies inherent in specialization and the failure to localize inherent in generality[18] (Bresnahan and Gambardella, 1998).

The tradeoff is clear in the paradigm case of the reuse of knowledge through more durable dies. In order to spread the knowledge contained in the dies over more and more units, enough people must be willing to consume the identical products stamped out. As Henry Ford insisted, you can have any color Model T you want as long as it's black. Indeed, Alfred Marshall was one of the first of

[17] Object-oriented programming involves a highly standardized and modularized form of code-writing that allows programmers to assemble code easily from preexisting pieces much as a child assembles a structure out of building blocks.

[18] I discuss below what the authors mean by a "general specialty."

many to attribute American economic growth in the nineteenth and early twentieth centuries to "the homogeneity of the American demand for manufactured goods," which enabled standardization and mass production (Marshall, 1920, I.viii.3, p. 146-7).

It is also possible, of course, to permit some variety while still reusing knowledge if the knowledge is applicable to more than one variant. In Cusumano's software-factory example, portions of code are reused in similar but not identical applications. General Motors pioneered an analogous strategy in the early automobile industry, using durable dies to stamp out standardized parts that went into a wide variety of slightly differentiated variant models (Raff, 1991) – a classic American idea that Marshall (1920, I.viii.2, p. 141) called "multiform" standardization. This kind of "flexible specialization" need not be limited to physical technology. In the early part of this century, the American medical profession responded to the size and integration of the American market by standardizing medical training and medical record-keeping in a way that equipped individual practitioners with a standardized "toolkit" of routines but allowed them the flexibility to apply those routines to widely varying concrete circumstances (Langlois and Savage, 2000).

Using the terminology of George Stigler (1951), Bresnahan and Gambardella (1998) have called attention to the role in economic growth of "general specialties," also called general-purpose technologies. A general specialty is a stage of production (specialized labor or tools) possessing knowledge or capabilities that are applicable to the production of many different outputs. Sometimes this is literally a technology, as in the case of the microprocessor, which, through software, can be adapted to many different uses. But the idea also presumably applies to knowledge more broadly, as in the case of American machine-tool capabilities in the early nineteenth century, which found application in a wide variety of mechanical industries (Rosenberg, 1976, p. 16).

Very clearly, institutions can serve the same economies-of-scope function; they are also general-purpose technologies in this sense. The more abstract the institution, the more general its applicability, and the more widely can the knowledge it contains be reused and spread across different and varied outputs. As Hayek (1973, p. 50) has said, abstract institutions consist of "rules applicable to an unknown and indeterminable number of persons and instances." Examples surely include language, law, social conventions, and even culture more broadly. All involve pieces of knowledge shared across many individuals and uses. All are, in effect, standards.

The key difference between knowledge embodied in (standardizing) institutions and knowledge embodied in replicated artifacts is that the former allows greater variety in the ways the knowledge is reused. This is so because the standard creates a framework in which variety can in effect be created by the consumer. To see the point, consider the provision of variety in *system products*, complicated goods or services consisting of many interacting components and subsystems. For many such goods, variety can come in the form of multiple preassembled packages.

For instance, there are significant economies of scale in the assembly of cars; but, relative to the size of the market, those economies are exhausted early enough that many different firms can profitably offer consumers many different models, each a distinct system product. In this example, the benefits of standardization come entirely from the economies of scale in production they enable. But, in other cases, standardization can have additional benefits that come not from the supply side but from the demand side. These benefits arise from the much-discussed phenomenon of *network effects*: the benefits to any individual of a would-be standard depend on how many other individuals already adhere (or are likely to adhere) to that alternative.[19] As more and more users commit to a standard, that standard becomes increasingly attractive to others; the commitment of those others makes the standard even more attractive – and so on in a cumulative fashion that is often described as "positive feedback." These are called network effects because, in the first instance, they arise in the case of physical connection networks like telephone systems. The value to me of a phone system increases with the number of other people who are on the system. But the concept has been applied to "virtual networks" in which the connections are not physical but rather in the nature of economic complementarity (Katz and Shapiro, 1985). For example, the benefit to consumers of a new digital television standard is proportional to the amount of programming they expect to be available on that standards, which is in turn dependent of the number of people who adopt the standard.

The dominance of a single standard may have its costs in foregone variety. Imagine a world in which manufacturers were all required to produce identical generic "people's cars" the parts for which were all standardized and interchangeable. Although there would likely be intense competition within the system by parts suppliers and assemblers, probably leading to significant modular innovation (Langlois and Robertson, 1992), the benefits of the standard would likely be outweighed by the costs in lost variety. Of course, saying that parts are interchangeable doesn't mean that they are all identical, and cars could be differentiated by the parts they use rather than by the overall design. To take a trivial example, one could plug in a high-quality car stereo system as easily as a low-quality one. But, in the case of automobiles, the fact of economies of scale in assembly and the lack of demand-side network effects suggest that variety is probably best provided in preset packages.

In many other systems, however, this is not the case. When there are low economies of scale in assembling a system, a modular structure, in which variety is provided through the choice of modules, can more thoroughly blanket the product space, and can do so in virtually a perfectly discriminating way (Langlois and Robertson, 1992). This point applies *a fortiori* to so-called hardware-software networks in which the "modules" are in the nature of software. Indeed, as a rough approximation, we might say that there is less of a tradeoff between variety and

[19] For recent surveys, see David and Greenstein (1990) and Economides (1996).

standardization the greater the extent to which variety is a matter of "software" rather than "hardware."

In part, this is a reflection of our perspective within the hierarchy of systems. Even if there are economies of scale in assembling major components of the system, there may not be economies of scale in offering variety in the system as a whole. For example, there are economies of scale in assembling televisions and videocassette recorders. But there are no such economies to hooking those components together and playing one of a wide variety of available tapes. Similarly, there are economies of scale in packaging variety in cars, but lower economies in packaging variety in the wider transportation system, since travel to different destinations using complementary modular assets like roads is a source of variety. Notice that, in both cases, it is the software rather than hardware – the tapes in one case and the destinations in the other – that creates much of the variety in the larger system. Of course, cars and (perhaps a lesser extent) video hardware nonetheless continue to provide some element of the variety, since different hardware can interact with the software to produce slightly different experiences. Driving through the Berkshires in a Porsche is not the same as driving there in a Chevy; watching Star Wars on a wide-screen TV is not the same as watching it on a 19-inch screen. In the case of personal computers, however, even the hardware can be varied by recombining modules.

These observations generalize from technological standards to standards *qua* institutions more generally. Although there would surely be a loss of variety in some sense if we were all to speak only one language, yet that one language would be capable of generating an infinite variety of "software." I can enjoy just as many destinations if I have to drive on the left and if green means stop. And inhabitants of the same "learning network" – to recall Wright's term – can generate a limitless variety of innovations.

5 Consumption

The "demand side" has entered our story so far only in a rather negative way. By craving variety, consumers reduce the ability of producers to standardize products and thus to spread knowledge overheads through embodiment in output. Two remarks are in order, however. First, consumers of intermediate goods (who are themselves producers and not final consumers) can also crave variety to the extent that similar outputs are produced in different ways in different places. Second, modern consumption theory sees even final consumers as producers who cobble together basic utility from various inputs (Lancaster, 1971; Stigler and Becker, 1977). Thus much of what I argued above applies easily to final consumption as well, even if there remain a few twists and turns.

Metin Cosgel and I have suggested that, although we should readily embrace the simile of consumption as production, we ought, however, to change our picture of how consumption is produced (Langlois and Cosgel, 1998). Rather than taking on board the conventional production-function approach, we should apply instead the theory of economic capabilities that is gaining currency in the theory of the firm (Teece and Pisano, 1994; Langlois and Robertson, 1995). In this view, the "production" knowledge required for consumption is not explicit and given, not contained in the mythical blueprints of neoclassical price theory. Instead, such knowledge is a matter of consumption routines, often tacit and acquired at a cost. As in the theory of the firm, one of the central issues in this revised theory of consumption is one of boundaries, that is, what kinds of routines will be generated within the consumption unit (the household) and what kinds imported from without

The assembled routines of consumers are a knowledge structure that, to be effective, must be compatible with other knowledge structures in society. In this case, the routines of consumers must mesh with those of producers (Langlois and Cosgel, 1998). In the long run this is not much of a problem, as each side has the incentive to adapt to the other. In the short run, however, major technological changes in the routines of consumption or (perhaps more typically) of production may necessitate major changes on the other side. Sometimes these changes are far from traumatic. Consumers arguably adapted easily to the introduction of branded packaged goods in the nineteenth century, even though these eliminated the role of intermediaries (like the butcher or the keeper of the general store) in measuring quantity and assuring quality (Chandler, 1977). But the change from mainframe computers to the decentralized client-server technology in the 1990s required a much more dramatic change in the routines of users, one that Bresnahan and Greenstein (1997) go so far as to label "coinvention."

6 Growth

At the American Economic Association meeting three years ago, Paul Romer described the worldview of the New Growth Theory this way.

> New growth theorists now start by dividing the world into two fundamentally different types of productive inputs that can be called "ideas" and "things." Ideas are nonrival goods that could be stored in a bit string. Things are rival goods with mass (or energy). With ideas and things, one can explain how economic growth works. Nonrival ideas can be used to rearrange things, for example, when one follows a recipe and transforms noxious olives into tasty and healthful olive oil. Economic growth arises from the discovery of new recipes and the transformation of things from low to high value configurations (Romer, 1996, p. 204).

I have tried here to take the contrary position that (1) this distinction is not true to the world and (2) it is not necessary to explain economic growth.

Knowledge often lives in things themselves, and just as often in the interstices between things and bit strings. These interstices are institutions. Growth is indeed about increasing returns, about the nonconvexities that arise when knowledge is produced once then reused many times. But the mechanism of knowledge reuse does not always – and perhaps does not mostly – involve knowledge transmission. Instead, the knowledge is reused by being imbedded in technology, organizations, and institutions. Although private rent-seeking behavior surely drives the engine, the process of knowledge creation is a social one, a kind of spontaneous order that arises not mostly from the directed search for knowledge but from the unintended effects of production and consumption. Knowledge creation is unmistakably endogenous to the economic process. But if we try to overlay a production function on this process, it would have to look more like the manna of an exogenous λ parameter than the result of rational optimizing behavior aimed at its creation. This is far from saying that we can't theorize about the process of knowledge creation and its role in economic growth. We have a lot of pieces of that theory. But they are not lying under the production-function lamppost.

"If new growth theorists have their way," writes Romer (1996, p. 206), "the first distinction economists will draw when looking at the physical world will be the one that separates rival things from nonrival ideas." If I have my way – admittedly, a far less likely possibility – economists will realize that things and ideas cannot be separated.

References.

Alchian AA (1959) Costs and output. In: Abramovitz M et al. (eds) The allocation of economic resources. Stanford University Press, Stanford. Reprinted in: idem (1977) Economic forces at work. Liberty Press, Indianapolis

Ames E, Rosenberg N (1965) The progressive division and specialization of industries. Journal of Development Studies 1(4): 363–383

Arora A, Gambardella A (1994) The changing technology of technological change: general and abstract knowledge and the division of innovative labour. Research Policy 23(5): 523–532

Arrow KJ (1962) Economic welfare and the allocation of resources to invention. In: Nelson RR (ed) The rate and direction of inventive activity: economic and social factors. Princeton University Press, Princeton

Arrow KJ (1974) The limits of organization. Norton, New York

Arthur WB (1988) Self-reinforcing mechanisms in economics. In: Anderson PW, Arrow KJ, Pines D (eds) The economy as an evolving complex system. Addison-Wesley, Reading, MA

Boisot Max H (1995) Information space: a framework for learning in organizations, institutions, and culture. Routledge, London

Boulding Kenneth E (1955) Notes on the information concept. Explorations (Toronto) 6: 103–112

Bresnahan TF, Gambardella A (1998) The division of inventive labor and the extent of the market. In: Helpman E (ed) General purpose technologies and economic growth. MIT Press, Cambridge

Bresnahan TF, Greenstein S (1997) Technical progress and co-invention in computing and the use of computers. In: Bailey MN, Reiss PC, Winston C (eds) Brookings papers on economic activity: microeconomics, 1996. Brookings Institution, Washington, DC

Chandler AD, Jr (1977) The visible hand. The Belknap Press of Harvard University Press, Cambridge

Cowan R, Foray D (1997) The economics of codification and the diffusion of knowledge. Industrial and Corporate Change 6(3): 595–622

Cowan R, David PA, Foray D (1999) The explicit economics of knowledge codification and tacitness. Working Paper 99-027, Stanford University

Cusumano MA (1991) Japan's software factories: a challenge to U.S. management. Oxford University Press, New York

Dasgupta P, David PA (1994) Toward a new economics of science. Research Policy 23(5): 487–521

David PA, Greenstein S (1990) The economics of compatibility standards: an introduction to recent research. Economics of Innovation and New Technology 1(1–2): 3–41

Dreyfus HL (1979) What computers can't do: the limits of artificial intelligence. Harper Colophon, New York
Dutton HI (1984) The patent system and inventive activity during the industrial revolution, 1750-1852. Manchester University Press, Manchester
Economides N (1996) The economics of networks. International Journal of Industrial Organization 14(2): 675–699
Edelman GM (1987) Neural Darwinism: the theory of neuronal group selection. Basic Books, New York
Edelman GM (1992) Bright air and brilliant fire: on the matter of mind. Basic Books, New York
Hayek FA (1952) The sensory order: an inquiry into the foundations of theoretical psychology. The University of Chicago Press, Chicago
Hayek FA (1973) Law, legislation and liberty, Vol I. University of Chicago Press, Chicago
Hayek FA (1978) New studies in philosophy, politics, economics, and the history of ideas. The University of Chicago Press, Chicago
Holland JH, Holyoak KJ, Nisbett RE, Thagard PR (1986) Induction: processes of inference, learning and discovery. MIT Press, Cambridge
Grossman GM, Helpman E (1991) Trade, knowledge spillovers and growth. European Economic Review 35(3): 517–526
Grossman GM, Helpman E (1994) Endogenous innovation in the theory of growth. Journal of Economic Perspectives 8(1): 23–44
Katz M, Shapiro C (1985) Network externalities, competition, and compatibility. American Economic Review 75(3): 424–440
Kimball DS (1929) Industrial Economics. McGraw-Hill, New York
Lamoreaux NR, Sokoloff KL (1999) Inventive activity and the market for technology in the United States, 1840-1920. NBER Working Paper No. W7107
Lancaster K (1971) Consumer demand: a new approach. Columbia University Press, New York
Langlois RN (1995) Do firms plan? Constitutional Political Economy 6(3): 247–261
Langlois RN (1997) Cognition and capabilities: opportunities seized and missed in the history of the computer industry. In: Garud R, Nayyar P, Shapira Z (eds) Technological innovation: oversights and foresights. Cambridge University Press, New York
Langlois RN (1999a) The coevolution of technology and organization in the transition to the factory system. In: Robertson PL (ed) Authority and control in modern industry. Routledge, London
Langlois RN (1999b) Scale, scope, and the reuse of knowledge. In: Economic organization and economic knowledge: essays in honour of Brian J. Loasby, Vol. I. Edward Elgar, Cheltenham
Langlois RN, Robertson PL (1992) Networks and innovation in a modular system: lessons from the microcomputer and stereo component industries. Research Policy 21(4): 297–313
Langlois RN, Cosgel MM (1998) The organization of consumption. In: Bianchi M (ed) The active consumer, pp 107–121. Routledge, London
Langlois RN, Robertson PL (1995) Firms, markets, and economic change: a dynamic theory of business institutions. Routledge, London
Langlois RN, Robertson PL (1996) Stop crying over spilt knowledge: a critical look at the theory of spillovers and technical change. Paper presented at the MERIT Conference on Innovation, Evolution and Technology, August 25-27, 1996, Maastricht, The Netherlands
Langlois RN, Savage DA (2000) Standards, modularity, and innovation: the case of medical practice. In: Garud R, Karnœ P (eds) Path creation and dependence. Lawrence Erlbaum Associates, Hillsdale, MI
Leijonhufvud A (1986) Capitalism and the factory system. In: Langlois RN (ed) Economics as a process: essays in the new institutional economics. Cambridge University Press, New York
MacKay DM (1969) Information, mechanism, and meaning. MIT Press, Cambridge
Machlup F (1983) Semantic quirks in studies of information. In: Machlup F, Mansfield U (eds) The study of information: interdisciplinary messages, pp 641-671. John Wiley, New York
Marshall A (1920) Industry and trade, 3rd edn. Macmillan, London
Mintzberg H (1979) The structuring of organizations. Prentice-Hall, Englewood Cliffs
Mitchell WC (1912) The backward art of spending money. American Economic Review 2(2): 269–282
Mowery DC (1995) Conclusion. In: Mowery DC (ed) The international computer software industry: a comparative study of industry evolution and structure. Oxford University Press, New York

Nelson RR (1992) What is ‘commercial’ and what is ‘public’ about technology, and what should be? In: Rosenberg N, Landau R, Mowery DC (eds) Technology and the wealth of nations, pp 57–71. Stanford University Press, Stanford
Nelson RR, Winter SG (1982) An evolutionary theory of economic change. Harvard University Press, Cambridge
North DC (1990) Institutions, institutional change, and economic performance. Cambridge University Press, New York
Polanyi M (1958) Personal knowledge. University of Chicago Press, Chicago
Raff D (1991) Making cars and making money in the interwar automobile industry: economies of scale and scope and the manufacturing behind the marketing. Business History Review 65(4): 721–753
Robertson PL, Alston LJ (1992) Technological choice and the organization of work in capitalist firms. Economic History Review 45(2): 330–349
Romer PM (1986) Increasing returns and long-run growth. Journal of Political Economy 94: 1002–1037
Romer PM 1990 Endogenous technological change. Journal of Political Economy 98: S71–S102
Romer PM (1996) Why indeed in America? Theory, history and the origins of modern economic growth. American Economic Review 86: 202–206
Rosenberg N (1976) Perspective on technology. Cambridge University Press, New York
Savage DA, Robertson PL (1999) The maintenance of professional authority: the case of physicians and hospitals in the United States. In: Robertson PL (ed) Authority and control in modern industry. Routledge, London
Saviotti PP (1998) On the dynamics of appropriability, of tacit and codified knowledge. Research Policy 26: 843–856
Shapiro C, Varian HR (1998) Information rules: a strategic guide to the network economy. Harvard Business School Press, Boston
Smith A (1976) An enquiry into the nature and causes of the wealth of nations, Glasgow edition. Clarendon Press, Oxford
Solow RM (1956) A contribution to the theory of economic growth. Quarterly Journal of Economics 70(1): 65–94
Stigler GJ (1951) The division of labor is limited by the extent of the market. Journal of Political Economy 59(3): 185–193
Stigler G, Becker G (1977) De gustibus non est disputandum. American Economic Review 67: 76–90
Swan TW (1956) Economic growth and capital accumulation. Economic Record 32: 334–361
Teece DJ, Pisano G (1994) The dynamic capabilities of firms: an introduction. Industrial and Corporate Change 3(3): 537–556
Weimer WB (1982) Hayek’s approach to the problems of complex phenomena: an introduction to the psychology of the sensory order. In: Weimer WB, Palermo D (eds) Cognition and the symbolic processes, Vol II. Lawrence Erlbaum, Hillsdale
Whitehead AN (1911) An introduction to mathematics. Henry Holt and Company, New York
Wright G (1999) Can a nation learn? American technology as a network phenomenon. In: Lamoreaux NR, Raff DMG, Temin P (eds) Learning by doing in markets, firms, and countries, pp 295–326. University of Chicago Press, Chicago