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Capital as Embodied Knowledge: Some Implications for the Theory of Economic Growth

HOWARD BAETJER, JR., HBaetjer@Towson.edu
Department of Economics, Towson University, 7800 York Road, Towson, Maryland 21252

Abstract. Capital goods are embodied knowledge of how to produce. Therefore, capital development is a learning process, through which knowledge gets embodied in new capital goods. Because the necessary knowledge is dispersed among many people who must interact to communicate their particular, often tacit knowledge, capital development is a social process. Because this interaction takes time and continually changes the capital structure, capital development is an on-going process. Capital development is a social learning process. Neither traditional nor "new" growth theory illuminates how the capital structure evolves. Traditional growth theory, by modeling capital as single variable in the production function, ignores the heterogeneity of capital goods and their varied structural relationships of complementarity, substitutability, feedback, and feed-forward. New growth theory, while accounting for technological change, still treats capital as aggregable and thus implicitly homogeneous. That capital development is a learning process suggests that growth rates can increase. What prevents exponential growth is neither diminishing returns nor upper bounds to human capital, as growth models assume. It is the constant challenge of maintaining capital complementarities in a world of incomplete and rapidly changing knowledge.

JEL classification: O40 and O30.

I. Introduction

The purpose of this paper is to understand better the nature of economic development, by studying the nature of capital and what that means for the process of capital development. Throughout the paper, by capital is meant capital goods—in Bohm Bawerk's words, "the produced means of production"—as opposed to financial or human capital.

The paper is in three sections. The first investigates the idea that capital is essentially knowledge, and what that implies for the process of new capital development. The next section examines and finds lacking the treatment of capital and capital development in traditional and "new" growth theory. A concluding section considers what the nature of the capital development process implies about the determinants of economic growth rates, in particular tendencies toward very rapid growth, and factors that check those tendencies.

Capital Goods as Knowledge; Capital Development as Learning

The research programme of which this article is part is motivated by the same question that motivated Adam Smith's *An Inquiry into the Nature and Causes of the Wealth of Nations* (1976): how do we account for human beings' economic advancement? How is it that our race of talking primates has been able to advance from barbarism to abundance, at least in certain areas of the world? What is the nature of the processes by which we are able, over time, to get more and better of the "necessaries and conveniencies of life" for the same amount of effort?

This paper's piece of this large inquiry takes as its point of departure that human society advances in economic well-being by increasing its productivity per person and by extending trade, and that these improvements depend on appropriate rules of conduct. Human advancement is thus an intertwined evolution of the capital structure, the catallaxy, and the common law. I focus on the first of these and ask, how does a society improve its productivity—its ability to produce more of the things it wants with a given amount of effort? It does so fundamentally *by increasing its knowledge of productive relationships, and building this knowledge into better tools*—better devices which extend people's physical, perceptual, and mental faculties for understanding and transforming the world they live in.[1]

What is the nature of this process? *How* do we build knowledge into better tools? That is the subject of this first section. We begin by considering what capital goods are. They are best understood not as physical things, but as knowledge—knowledge which happens to be embodied in those physical things. The distinction is a matter of emphasis, but an important one for understanding the processes by which we develop and improve the capital goods on which our standard of living depends.

Capital Goods as Knowledge

There is a fundamental relationship between knowledge and capital. Indeed, capital *is* embodied knowledge of productive processes and how they may be carried out. Different varieties of knowledge are involved, as well as different kinds of embodiment.

Embodied Knowledge. Menger writes, "The quantities of consumption goods at human disposal are limited only by the extent of human knowledge of the causal connections between things, and by the extent of human control over these things" (1981:74). As this statement comes in a passage contrasting simply collecting first-order goods with employing goods of higher order in production processes, it is clear that we are to take the use of higher-order goods—capital goods—as the application of the knowledge Menger speaks of. When we know how to produce in a roundabout way, we employ capital goods for the purpose. Our knowledge is to be found in practice not in our heads, but in the capital goods we employ. Capital is embodied knowledge.[2]

In particular, capital equipment—tools—embodies knowledge of how to accomplish some purpose.[3] Much of our knowledge of the causal relationships between things, and of how to effect the changes we desire, is not articulate but *tacit* knowledge. Adam Smith speaks of the "skill, dexterity, and judgment" (p. 7) of workers; these attributes are a kind of knowledge, a kinesthetic "knowledge" located in the hands rather than in the head. The improvements these skilled workers make in their tools are embodiments of that knowledge. The very design of the tool passes on to a less skilled or dexterous worker the ability to accomplish good results. Consider how the safety razor enables those of us unskilled in the barber's craft to shave with the blade always at the correct angle, rarely nicking ourselves.

The skilled barber's dexterity has been passed on to us, as it were, embodied in the design of the safety razor.

Adam Smith gives a clear example of the embodiment of knowledge in capital equipment in his account of the development of early steam engines, on which:

> a boy was constantly employed to open and shut alternately the communication between the boiler and the cylinder, according as the piston either ascended or descended. One of those boys, who loved to play with his companions, observed that, by tying a string from the handle of the valve which opened this communication to another part of the machine, the valve would open and shut without his assistance, and leave him at liberty to divert himself with his playfellows (p. 14).

The tying on of the string, and the addition of the metal rod which was built on to subsequent steam engines to accomplish the same purpose, is an archetypal case of the embodiment of knowledge in a tool. The boy's observation and insight were built into the machine for use indefinitely into the future.

Knowledge is of the Essence. The point here is more radical than simply that capital goods have knowledge in them. It is rather that capital goods *are knowledge*, knowledge in the peculiar state of being embodied in a form ready-to-hand for use in production. The knowledge aspect of capital goods is the fundamental aspect. Any physical aspect is incidental.

A hammer, for instance, is physical wood (the handle) and minerals (the head). But a piece of oak and a chunk of iron do not make a hammer. The hammer is those raw materials infused with the knowledge embodied in the precise shape of the head and handle, the curvature of the striking surface, the proportion of head weight to handle length, and so on. (We leave aside, for now, all the additional knowledge required to shape the oak into a handle and the iron into a steel head.)

Even with a tool as bluntly physical as a hammer, the knowledge component is of overwhelming importance. With precision tools such as microscopes and calibration instruments, the knowledge aspect of the tool becomes more dominant still. We might say, imprecisely but helpfully, that there is a greater proportion of knowledge to physical stuff in a microscope than in a hammer.

With computer software we have a logical extreme to inform this approach to understanding capital goods. Software is less tied to any physical medium than most tools. Because we may with equal comfort think of a given program *as* a program, whether it is printed out on paper, stored on a diskette, or loaded into the circuits of a computer, we have no difficulty distinguishing the knowledge aspect from the physical aspect with a software tool. Of course, to *function* as a tool the software must be loaded and running in the physical medium of the computer, and there are definite physical limits to computation (Bennet 1985). Nevertheless, it is in the nature of computers and software to separate clearly the *knowledge* of how to accomplish a certain function from the *physical embodiment* of that knowledge.

The distinctness of the knowledge embodied in tools from the physical medium in which it is embodied was brought out in a remarkable exchange between two engineers working on a moonshot years ago. One, a rocket engineer responsible for calculating propulsion capacity, approached the other, a software engineer. The rocket engineer wanted to know how to calculate the effect of all that software on the mass of the system. The software engineer didn't understand; was he asking about the weight of the computers? No, the computers' weight was already accounted for. Then what was the problem, asked the software engineer. "Well, you guys are using hundreds of thousands of lines of software in this moonshot, right?" "Right," said the software engineer. "Well," asked the rocket scientist, "how much does all that stuff weigh?" The reply: ". . . Nothing!!"[4]

Because the knowledge aspect of software tools is so clearly distinguishable from their physical embodiment, in investigating software capital we may distinguish clearly the knowledge aspects of capital in general. While software may seem very different from other capital goods in this respect, when we think in terms of the capital structure, we find no fundamental difference between software tools and conventional tools. What is true of software is true of capital goods in general. What a person actually uses is not software alone, but software loaded into a physical system—a computer with a monitor, or printer, or plotter, or space shuttle, or whatever. The computer is the multi-purpose, tangible complement to the special-purpose, intangible knowledge that is software. When the word-processor or computer-assisted design (CAD) package is loaded in, the whole system becomes a dedicated writing or drawing tool.

But there is no important difference in this respect between a word-processor and, say, a hammer. The oaken dowel and molten steel are the multi-purpose, tangible complements to the special-purpose, intangible knowledge of what a hammer is. When that knowledge is imprinted on the oak in the shape of a smooth, well-proportioned handle, and on the steel in the shape, weight, and hardness of a hammer-head; and when the two are joined together properly; then the whole system—raw oak, raw steel, and knowledge—becomes a dedicated nail-driving tool.

All tools are a combination of knowledge and matter. They are knowledge imprinted on or embodied in matter. Software is to the computer into which it is loaded as the knowledge of traditional tools is to the matter of which those tools are composed.

If this is true, then knowledge is the key aspect of all capital goods, because the matter is, and always has been, "there." As Bohm-Bawerk says in discussing what it means to produce:

> To create goods is of course not to bring into being materials that never existed before, and it is therefore not creation in the true sense of the word. It is only a conversion of indestructible matter into more advantageous forms, and it can never be anything else (1959:7).

Mankind did not develop its fabulous stock of capital equipment by acquiring new quantities of iron and wood and copper and silicon. These have always been here. Mankind became wealthy through developing the knowledge of what might be done with these substances, and building that knowledge into them. The value of our tools is not in their weight of substances, however finely alloyed or refined. It is in the quality and quantity of knowledge imprinted on them. As Menger says in his *Principles*:[5]

> Increasing understanding of the causal connections between things and human welfare, and increasing control of the less proximate conditions responsible for human welfare, have led mankind, therefore, from a state of barbarism and the deepest misery to its present stage of civilization and well-being. . . . Nothing is more certain than that the degree of economic progress of mankind will still, in future epochs, be commensurate with the degree of progress of human knowledge.

Varieties of Knowledge Embodied in Capital. In the above passage Menger asserts a dependency of economic progress on progress of human knowledge. This sounds simple. Perhaps it would be simple if knowledge were a simple, homogeneous something which could be pumped into a society as fuel is pumped into a tank. But knowledge is heterogeneous; it is not all of a kind (Polanyi 1958, Hayek 1945, Lachmann 1986). There are important differences among different kinds of knowledge.

Articulate and Inarticulate Knowledge. An important distinction in this respect is between articulate and inarticulate knowledge. Some of our knowledge we can articulate: we can say precisely what we know, and thereby convey it to others.[6] But much of our knowledge is inarticulate: we cannot say what we know or how we know it. Hence we cannot explicitly convey that knowledge to others, at least not in words. The experienced personnel officer cannot tell us how she knows that a certain applicant is unfit for a certain job; she has "a feel for it." The skilled pianist cannot possibly tell us how to play with deep expressiveness, although he clearly knows how. A child cannot learn to hit a baseball from reading about it in a book, although the book might help.

Furthermore, much of what we know we are not aware that we know. In such cases we do not become consciously aware of our knowledge until it is somehow brought to our attention, perhaps by our being asked to behave in a way that conflicts with that knowledge. "Let's do such and such," we are asked. "No, that won't work," we reply. "Why not?" "Well, it won't..," we say, but we can't really say why until we have had time to think about it, and become explicitly aware, for the first time, of what we have long known. In this respect I remember my high school physics teacher telling our class that we all "knew" the Doppler effect—that the sound made by a moving object sounds higher pitched to us when the object is approaching, and sounds lower-pitched when the object is moving away. He smiled and made the sound every child makes when imitating a fast car going past. Sure enough, the pitch goes from higher to lower—of course, I knew that; but I had not known that I knew it.

Personal and Intersubjective Knowledge. There is also an important variety in what we may call the locations of knowledge. It may be internal—located within a person—or external, embodied in some *intersubjective* medium—located, as it were, among people, and therefore available for common use. In both kinds of these "locations" there can be both articulate and inarticulate knowledge.

I know my own verbalized thoughts and plans for the day, facts I learned in school, my phone number, etc. This is personal, articulate knowledge. Much articulate knowledge is of course located externally, intersubjectively, in a form in which it can be transferred among people. This is the case with books, libraries, manuals, "for sale" signs, engineering formulae, blueprints, recipes, etc.

Similarly, there are both personal and intersubjective forms of *inarticulate* knowledge. Personal inarticulate knowledge we mentioned above, e.g. personal skills, habits, rules of thumb. *Interpersonal* inarticulate knowledge comprises much of the knowledge most important to successful social interaction. Social institutions embody this kind of knowledge. Language, for example, embodies a great deal of shared knowledge, accumulated over ages through interactions among people. As F.A. Hayek has stressed, there is a tremendous amount of knowledge in market prices (1945). Don Lavoie has developed this view (1985, Chapter 3), speaking of a "social intelligence" that emerges out of the interactions of people, which the society as a whole has, but no individual has.

In this category of inarticulate knowledge located external to individuals, and thus available to be shared among individuals, is much of the knowledge embodied in tools. The crucial knowledge referred to by Menger above is of a kind we don't often think of as knowledge. It is not to be found in libraries or in books or in written words at all. Rather it is to be found in the designs of the tools we use. Much of it is inarticulate. Some may once have been articulated, but the articulation is now lost. Much may never have been articulated at all. Consider, for example, the ratio between the weight of a hammer head and the length of the handle. Hammer makers "know" the acceptable bounds of this ratio. How do they know? They know because the experience of generations has been handed down to them. Users of hammers, ages ago, found hammers with handles too long or too short to be uncomfortable; they discarded these and used the proper-sized ones instead. They could not have said why they did so—they knew with their hands and arms, not with their heads. When they selected new hammers, they chose the ones with the "correct" ratio. From these choices hammer makers learned what the correct ratio was. The knowledge was gradually built into hammers over time, in an evolutionary fashion that depended on feedback from users.

A significant proportion of the knowledge we use in production is not in any person or even group, but in the tools we use. I who use the hammer know nothing of ergonomics, and have not the slightest idea what the "correct" ratio of head weight to handle length is. Nevertheless, when I drive a nail, I can tell if the hammer feels right. Thus I use that knowledge. The knowledge is built into my hammer.

Capital goods, then, are embodied knowledge of how to accomplish productive purposes. This fact has important implications for how we treat capital in theories of economic growth. This subject will be treated at some length in section II, but let us anticipate slightly here by noting how different this approach is from that taken in mainstream growth theory, both traditional and "new":

Traditional growth theory treats capital as a stock of undifferentiated physical stuff. (Rarely does the "old" or Solovian growth theory even distinguish between financial capital and capital goods, as if the investments entrepreneurs make in particular hardware and software systems are automatic and riskless.) New capital added to that stock in any period consists of last period's unconsumed output. Modeling capital as magnitudes of k, traditional growth theory treats capital as homogeneous and measurable. Thus it emphasizes the quantitative *physical* aspect of capital—numbers of machines and tons of chemicals—rather than the knowledge aspect.

New growth theory models, while some do differentiate kinds of capital goods, continue to separate technology and capital. Typically technology gets developed in a research sector separate from the actual production of capital goods, and technology and capital enter the models' equations as *separat*e variables. This approach is inconsistent with the present view that capital goods embody their technology, that the two cannot be separated, actually or conceptually.

From our viewpoint, these approaches obscure what capital is, in a manner that obscures the process by which it is developed.

Capital Goods and Division of Knowledge Across Time and Space

The previous section stressed that capital embodies knowledge. The point of this section is the *social* character of that knowledge. The knowledge of *lots of people* is combined in capital goods; hence capital development is a process of *social* interaction, not a matter of individuals working autonomously. Most individual capital goods are manifestations of a far-flung division of knowledge, an almost incomprehensibly extensive sharing of the knowledge and talents of thousands of people across time and space. The ever-changing pattern of relationships among these capital goods—the capital structure as a whole—is an essential aspect of what Hayek called "the extended order of human cooperation."

Capital goods and the capital structure at any time result from a tremendously rich social interaction through which the knowledge of many has been combined. To pursue this idea further, let us consider Adam Smith's discussion of the division of labor, to which he attributed the lion's share of human progress.

Recall Smith's case of improvement to the steam engine, which grew out of a small boy's observation that he could tie a piece of string from the handle he was assigned to operate to another part of the machine, and so get the action of the machine to do his job for him. Subsequently this insight was built into the design of steam engines. When, in cases such as this, knowledge is built into a piece of capital equipment so thoroughly that an actual person is no longer required, what has happened to the division of labor? Has it decreased? The little boy is no longer at work at the steam engine. Does his departure diminish the division of labor present in that production process? Are there fewer people contributing?

It appears that what Adam Smith meant by the division of labor was the division, among a number of different people, of all the tasks in a particular production process. Given a number of tasks which are *visibly* part of the production process, the fewer the instances in which the same person carries out more than one of those tasks, the greater the division of labor. This view is evident in Smith's remarks on agriculture:

> The nature of agriculture, indeed, does not admit of so many subdivisions of labour, nor of so complete a separation of one business from another, as manufactures. It is impossible to separate so entirely, the business of the grazier from that of the corn-farmer, as the trade of the carpenter is commonly separated from that of the smith. The spinner is almost always a distinct person from the weaver; but the ploughman, the harrower, the sower of the seed, and the reaper of the corn, are often the same (1976:9–10).

Here Smith focuses on division of labor among those directly involved in a production process: how many laborers are involved at that time and place, *given the tools they have*.

We take issue with Smith, holding that the division of labor is better understood as the whole pattern of cooperation in production, direct and indirect. The indirect contributions—in the form of tools and processes developed elsewhere—are, in an advanced economy, the most significant. There is a deep, rich social interaction represented in the capital goods with which any individual works. As Carl Menger pointed out, the crucial "labor" is the creative effort of learning how,[7] and the embodying of that learning in a tool design that can be used by others, who themselves lack the knowledge in any other form. We really do better to speak of the division of knowledge rather than the division of labor.

Axel Leijonhufvud makes clear the importance of the division of knowledge in his article, "Information Costs and the Division of Labor" (1989). He invites us to consider a medieval serf, named Bodo, and asks "Why was he poor?" Leijonhufvud argues, "Bodo was poor because few people co-operated with him in producing his output and, similarly, few people co-operated in producing his real income, i.e. in producing for his consumption" (p. 166). The cooperation need not be on the same spot and at the same time to be relevant. Indeed, as an economy advances, the pattern of cooperation spreads out spatially and in time.

> Our rich twentieth century representative man, then, occupies a node in a much larger network of co-operating individual agents than did poor Bodo. His network, moreover, is of very much larger spatial extent. The average distance from him of those who contribute to his consumption or make use of his productive contribution is longer. Similarly, his network also has greater temporal depth—the number of individuals who *t* periods into the past made a contribution to his present consumption is larger than in Bodo's case (Leijonhufvud 1989:166).

The ongoing development of advanced capital goods is an intensely social activity. In his comments on the division of labor in agriculture, Smith neglects the division of knowledge and of labor implicit in the tools the farmers use. The plow, the harrow, and the scythe (or in our day the John Deere combine[8]), themselves represent an extensive division of labor and, more importantly, of knowledge. To be consistent with his suggestion in the quoted passage, Smith would have to assert that there is less division of labor represented in the present day manufacture of pins, in which (if I guess correctly) hundreds of thousands may be made in a day in a fully mechanized process overseen by one technician at a computer terminal, than in the factory of which he wrote. But the fact that there is now only one person there on the spot does not mean there is no division of labor in pin making. It illustrates, rather, that the division of labor is now more subtle: it is manifested not in many workers, but in very sophisticated tools to which many creative workers have contributed their special knowledge of the steps (what used to be the individual *tasks*) involved in pin-making. Today's equivalent of Smith's division of labor is manifested in a complex division of knowledge embedded in a deep pin-making capital structure.

As Thomas Sowell has observed, "the intellectual advantage of civilization ... is not necessarily that each civilized man has more knowledge [than primitive savages], but that he *requires* far less" (1980:7, emphasis in original). Through the embodiment of knowledge into an extending capital structure, each of us is able to take advantage of the specialized knowledge of untold others who have contributed to that structure. The structure becomes increasingly complex over time, as the pattern of complementary relationships extends.[9]

In capital-intensive, modern production processes, the division of knowledge and labor is to be found not in the large number of people at work in a particular production process, but in the tools used by a relatively few people who carry out that process. *The knowledge contribution of multitudes is embodied in those tools*, which give remarkable productive powers to the individual workers on the spot. The little boy is there in a modern steam engine, his knowledge embodied in the valve-control rod. The farmer at his plow is empowered by the knowledge and labor of hundreds of others, who designed his plow and hardened its steel, who developed his tractor, who learned how to refine its fuel, etc.

The point is emphasized by Bohm-Bawerk, who in the following passage could be responding to Smith's above comments on agriculture:

> . . .the labor which produces the intermediate products . . . and the labor which produces the desired consumption good from and with the help of the intermediate products, contribute alike to the production of that consumption good. The obtaining of wood results not only from the labor of felling trees, but also from that of the smith who makes the axe, of the carpenter who carves the haft, of the miner who digs the ore from which the steel is derived, of the foundryman who smelts the ore. Our modern system of specialized occupations does, of course, give the intrinsically unified process of production the extrinsic appearance of a heterogeneous mass of apparently independent units. But the theorist who makes any pretensions to understanding the economic workings of the production process in all its vital relationships must not be deceived by appearances, his mind must restore the unity of the production process which has had its true picture obscured by the division of labor (1959, II, p. 85).

What a difference there is between the meaning Bohm-Bawerk attaches to the division of labor in this passage and the view suggested by Adam Smith in his comments on agriculture. For Bohm-Bawerk, the division of labor is extended down time and across space. The miner of the ore is "there," in a sense, as the lumberjack fells trees with steel made from that ore. In an advancing economy, the division of knowledge is an ever-widening system of cooperation in which are developed new tools and processes whereby each person may take advantage of the knowledge of an increasing number of his or her fellows. The division of knowledge is manifested in the tools we work with, which embody the knowledge of many.

Capital Structure

Understanding of the nature of capital development requires a clear appreciation that capital goods work and have value in particular relationships with one another—in the capital structure (Lachmann 1978, Hayek 1941). New tools contribute to the economy not by being thrown, as it were, into a bubbling economic pot, where one ingredient adds as much to the amorphous stew as another. Rather they each must fit into a structure, or, more aptly, they must play a particular role in particular niche in a kind of economic ecosystem (Rothschild, 1990). If they are ill adapted to their niches, they make no contribution, fail to sustain themselves, and are selected out.

Capital exists and works within a structure. It is an ever-evolving structure to be sure—it is never static—but throughout its evolution the relationships among capital goods, and among capital goods and human capital, are essential. Of the various perspectives we might take on the capital structure, two will be important to us. One looks at the relationships of complementarity between capital goods used jointly in a production process; another looks at relationships of dependency between capital goods, one or more of which are used in producing another.

Complementarity of the Essence. Ludwig Lachmann writes,

> It is hard to imagine any capital resource which by itself, operated by human labour but without the use of other capital resources, could turn out any output at all. For most purposes capital goods have to be used jointly. *Complementarity* is of the essence of capital use. But the heterogeneous capital resources do not lend themselves to combination in any arbitrary fashion. For any given number of them only certain modes of complementarity are technically possible, and only a few of these are economically significant (p. 3, emphasis in original).

Most programming languages run only on certain kinds of computers. Many require further that the computer be equipped with a mouse, a high-resolution display, certain minima of RAM and disk space, and perhaps a math co-processor. Various graphical user interface builders run only on certain specific versions of particular programming environments. These are very powerful tools, but usable only if the necessary complementary goods are present. None of them, of course works at all with such other capital goods as, say, tractors, diesel fuel, and plows, which have their own complementary relationships.

The challenge of capital *maintenance* has fundamentally to do with complementarity. Capital exists and functions in a capital structure that *evolves over time* as old tools and processes are supplanted by new. Consequently, for any particular (kind of) capital good, maintenance is very much a matter of maintaining its complementarity to the rest of the changing capital structure. Hence maintenance may have to do not so much with preventing any change through deterioration, as with actually changing that (kind of) good directly, in a manner that adapts it to the changing capital structure around it, and thereby delays obsolescence.

Because change is pervasive, how a particular (kind of) capital good is used will inevitably change. As Hayek has pointed out (1935), capital maintenance is often more a matter of maintaining the value of capital than merely preventing decay. But because value depends on position in a changing capital structure, maintaining value may mean changing the good more than preserving it as is.

Software, of course, does not deteriorate. (A diskette may, but a diskette is software's storage medium, not software itself.) Yet programmers speak of "bit rot," that creeping incompatibility that erodes software's usefulness as the environment changes—with new computers, peripherals, operating systems, etc.—and the code does not. This is purely a matter of complementarity. To maintain the value of a piece of software, even when what it does stays exactly the same, requires changing that software to keep it complementary to the changing capital goods with which it must work.

Orders of Capital Goods. An important aspect of the capital structure is orders of goods,[10] consumer goods being goods of the first order, and capital goods being goods of higher orders. As the capital structure lengthens, we develop tools for producing tools for producing tools and so on. The better the tools at each stage, the better and more cheaply we may produce the goods at the next lower stage. Menger stressed the importance of lengthening the capital structure:

> Assume a people which extends its attention to goods of third, fourth, and higher orders. . . If such a people progressively directs goods of ever higher orders to the satisfaction of its needs, and especially if each step in this direction is accompanied by an appropriate division of labor, we shall doubtless observe that progress in welfare which Adam Smith was disposed to attribute exclusively to the latter factor (p. 73).

Improvements in tools (and related processes) of high order are very important to economic development, because those improvements can be leveraged throughout the production process.[11]

Frequently, there is a kind of recursion involved, in that developments at one stage make possible developments at another stage, which can in turn improve processes at the first stage. Better steel, for example, the product of a steel mill, makes possible the construction of better steel mills. The availability of the programming language Smalltalk made possible the user interface builder WindowBuilder, which was itself an improvement to the Smalltalk programming environment.

Capital Development as a Social Learning Process

We are now in a position to draw some conclusions about the nature of capital development—the process by which people, over time, develop better, faster, cheaper tools with which to provide themselves with "the necessaries and conveniencies of life."

As our attention is on developing new and better tools, we must focus on how people develop new *designs* for goods, as distinguished from how they produce individual instances—real cases—of those designs. The production processes are very different. Living as we do in a physical world, where physical instances catch our eye, it is easy to overlook the production of designs, and see only the production of instances. Economics, certainly, has overlooked the production of designs, by and large assuming it away: standard models assume "given technology" or use of the "best available technology." But for our purposes—investigating how the capital structure develops and improves—it is essential to focus on production of designs as an activity different from production of particular goods embodying those designs.

Contrast our common conceptions of producing cars, on the one hand, and of producing software, on the other. When we think of GM producing cars, we think of their work creating new *instances* of extant designs. True, GM employs many designers, who *design* new cars, but we don't think of that; we think of the assembly line, spot welding, riveting, bolting, etc. We think of the *physical* work of *realizing* these designs—imprinting a design on metal and rubber and glass so that a new instance of the design—a new car—comes to be.

When we think of Microsoft's work producing software, by contrast, we think of programmers writing code—creating new designs (or enhancing older designs). True, Microsoft employs people who store the programs onto diskettes, thus in a sense creating instances of the extant designs; but we don't think of that; we think of the late nights at the terminal designing, coding, revising, running, debugging, etc. We think of the *mental* work of creating new software—new *designs*, specific instances of which will eventually be copied in mass onto diskettes and distributed.

The point here is not that design is unimportant in heavy industries such as automobile manufacturing.[12] Not at all. In fact, we hold that design is just as important in heavy industries as in software. Indeed, by way of example, the design process for the GM-10 line of cars at General Motors was allocated $7 billion and five years.[13] The point is simply that design of capital goods and what we will call their *instantiation*—the creation of actual instances of those designs—are fundamentally different. Instantiation is concerned with the known, design with the unknown. Instantiation is a matter of imprinting a design onto a different medium; design is a matter of bringing together knowledge of how to accomplish productive purposes that has not yet been brought together in that manner.

What then, can we say about the nature of capital good development, given what we know of capital goods as such?

First, because capital is embodied *knowledge*, capital development is a matter of *learning*, through which the knowledge gets embodied in the new good.[14] Second, because the necessary knowledge is *dispersed* among many different people who must interact to communicate their particular and often tacit knowledge, capital development is a matter of *social interaction*. Third, because this interaction takes time and because the capital structure changes as learning occurs, capital development is an on-going *process*. In brief, because capital is embodied knowledge, capital development is a *social learning process*.

II. Absence of Capital Development in Extant Growth Theory

Because improvements in tools and tool systems are so important to economic development and growth, one might expect to find insight into how tool systems evolve in the branch of economics known as the theory of economic growth. But growth theory, both the traditional and the "new growth theory," is engaged in a different kind of inquiry. Growth theory has very little to say about the development of the new and better tools we ultimately depend on for economic advancement—the development of the capital structure.

Problematic Aspects of Traditional Growth Theory: The Harrod-Domar-Solow Approach

At the center of neoclassical growth theory is the Harrod-Domar approach, which was elaborated by Robert Solow in work that helped win him the Nobel Prize. Although this body of work refers to capital extensively, it says very little *about* capital, and nothing about how the capital structure evolves. In fact, it assumes that the capital structure does *not* evolve in any *qualitative* way. There are three closely interrelated assumptions in this theory which necessarily eliminate consideration of actual improvements to capital goods and the capital structure.

It Ignores the Heterogeneity of Capital. A fundamental problem with the Harrod-Domar-Solow strand of growth theory for our purposes is that it treats capital as homogeneous. In Harrod's model, capital is a homogeneous stuff that can be accumulated incrementally. The "actual saving in a period . . . is equal to the addition to the capital stock,"[15] Harrod tells us. This indicates that quantities of "capital" may be indefinitely built up. Solow's discussion of the model makes this more explicit: he defines "the stock of capital" as "the *sum* of past net investments" (1970:4, emphasis added), and says that the "capital requirement per unit of output [is a] fixed number . . . in the sense that [it does] not change in the course of time" (1970:9). Capital is not only homogeneous in time, according to Solow, but also homogeneous across time.

This mechanical approach to capital treats it like a multiplier: more capital means a bigger number multiplying the effort of labor. E.g., if we have 100 units of K at time 0, and, say, 5 laborers, then we get $5 \times 100 = 500$ units of output. Then we take some savings from that output and (less depreciation) add it to the 100. Suppose net savings are 3, then in period 1 we have $5 \times 103 = 515$ units of output. Capital is essentially all of the same kind and quality. Its value is its purchase price; it can be increased only *quantitatively*. Given fixed input of human effort, getting more output with the same "amount" of capital is not possible.

But capital in the world is not homogeneous. As Ludwig Lachmann points out, "*capital resources are heterogeneous*. . . While we may add head to head . . . and acre to acre . . . we cannot add beer barrels to blast furnaces nor trucks to yards of telephone wire" (Lachmann 1978:2). Furthermore,

> for most purposes capital goods have to be used jointly. *Complementarity* is of the essence of capital use. But the heterogeneous capital resources do not lend themselves to combination in any arbitrary fashion (1978:3).

Some capital combinations are useless: beer barrels and blast furnaces, for example. But other combinations multiply the value of one another, e.g., fertile fields and advanced farm machinery. To quote from Lachmann again,

> The theory of capital must therefore concern itself with the way in which entrepreneurs form combinations of heterogeneous capital resources in their plans, *and* the way in which they regroup them when they revise these plans. A theory which ignores such regrouping ignores a highly significant aspect of reality: the changing pattern of resource use which the divergence of results actually experienced from what they had been expected to be, imposes on entrepreneurs (1978:35).

The theory of capital must also concern itself with the way in which entrepreneurs develop new, different, and better heterogeneous capital resources.

We note in passing that the Harrod-Domar-Solow theory not only fails to differentiate between kinds and orders of capital, it also declines to differentiate even between capital goods and consumption goods. Harrod states that, "No distinction is drawn in this theory between capital goods and consumption goods. In measuring the increment of capital, the two are taken together; the increment consists of total production less total consumption"

(p. 18). This is another way of saying that saving equals investment, and that all savings automatically become capital goods. This failure to distinguish between the different categories of goods produced leads Harrod to such remarkable statements as, "a condition of general over-production is the consequence of producers in sum producing too little" (p. 24). In Solow's development of Harrod's work the blurring of capital goods and consumption goods is made even more explicit: "The model economy produces only one composite commodity, which it can either consume currently or accumulate as a stock of capital."[16]

Perhaps there are purposes to be served by modeling production in this way, but for understanding how we develop new and better means of producing the things we want, a theory that assumes away differences between the things we want and the means of producing them is not useful.

It Assumes Quantifiability of Capital. Traditional growth theory also relies on a mathematical treatment of capital: capital appears in the models as a numerical variable in a production function. Such a treatment implies that capital can be meaningfully quantified—measured in some way. Harrod, for example, speaks of "the value of . . . capital goods" (p. 16) and posits that "actual saving in a period . . . is equal to the addition to the capital stock" (p. 18). The terminology gives the impression that capital can be easily measured, and the equations depend on the economy's capital stock being quantifiable.

But capital is ultimately unmeasurable.[17] As Harrod's colleague Joan Robinson observed, "no one ever makes it clear how capital is to be measured."[18] Israel Kirzner addresses the immeasurability of capital in his *An Essay on Capital* (1966).[19] First he dispenses with the idea that capital can be measured in raw physical terms.

> The truth is that the heterogeneity of the various physical items in the stock not only constitutes a well recognized barrier to the construction of such a measure, but represents at the same time the reason why such a measure can play no significant role at all in the analysis of decision making in the course of capitalistic production. The producer simply cannot afford to ignore the heterogeneity of the various items in the capital stock (p. 105).

Kirzner then turns to "backward-looking" measures of the existing capital stock: the past sacrifices—the costs—involved in building up that stock. This is the kind of measure most in accordance with the Harrod-Domar-Solow methodology, since they declare the value of new capital to be that of the output not consumed in a period. Kirzner points out that these past costs are generally of different kinds and made at different dates; accordingly they cannot be meaningfully summed. Likewise "forward-looking" measures of capital are unsatisfactory. These are the efforts "to measure the capital stock by the contribution to future production that it is able to make" (p. 113). With these measures there are a number of difficulties, the most important being that future value depends on many individuals' plans for the capital (which has alternative uses), and that these plans may be mutually inconsistent. "[I]t is in many respects a misleading simplification to talk as if a given resource were unambiguously associated with a definite flow of output, in the sense that such an output flow is forthcoming automatically from the resource" (p. 114).

The point here is not simply that it is technically difficult to quantify the amount or the value of capital, but that the notion of an amount of capital has at best an extremely imprecise meaning. It is imprecise even as an accounting measure within a firm, where plans for the use of different pieces of capital can be kept more or less compatible. But as the level of aggregation increases, the imprecision grows rapidly. "The amount of capital" is at best a useful mental shorthand. Treating it as if it were precise, in a mathematical equation, is more likely to confuse than to clarify.

It Assumes a Fixed Functional Relationship Between Aggregate Capital and Output. The two problems mentioned above—the twin assumptions of homogeneity and of quantifiability of capital—are probably consequences of this third: that the theorists are determined to represent the relationship between capital and output as a functional relationship, *in which the function itself is not allowed to change*. To model production in a functional relationship with capital necessitates an interpretation of capital as homogeneous, so that it may be aggregated meaningfully, and as quantifiable (at least in principle), so that this aggregation may be represented by a numerical variable.

The only place Harrod's model[20] might admit changes in the quality of people's tools, and hence in the production function, is in C, the "capital coefficient," defined as "the value of the capital goods required for the production of a unit increment in output." But as Harrod presents C, changes in its value are unimportant. While he tells us that C can change, beyond vague references to "the state of technology" we are given no indication of how, when, or why it might do so. More importantly, in Harrod's actual description of the workings of the economy, he allows for no adjustments in technology. The only kind of adjustment his model allows to producing agents is a change in how much they produce—by the same technology. If, for example, producers find that they have not sold all of their output in one period, they respond by cutting back production in the next period; these cutbacks are general (because there are no different kinds of goods), and therefore the economy falls off Harrod's famous "knife-edge." What producers never do, in a Harrod world, is react to poor sales by improving their tools so that next year they can produce at lower cost and sell all their output by offering it at a more attractive lower price.

For Solow, the fixed relationship between capital and output is made quite explicit: "the capital/output ratio is . . . constant—this is one of the defining characteristics of a steady state. . . (p. 33). Solow assumes constant returns to scale (p. 34), and contrives the model so that "technological progress augments labor only" (p. 35). That is, technological progress improves what human workers can do, not what their machines and devices can do. Increasing advances in productivity per person resulting from new capital goods are ruled out. In a Solow world there can be no fine new machines with which a company may, over time, double and triple its output without increasing its work force.[21]

The problem with an unchanging production function (let alone a function with constant returns to scale) is that it rules out change in *how* things are done. But again, our inquiry is concerned with how we come to develop new tools and methods, which means new and different ways of producing—a *different* "production function." Further, given the unfathomable complexity of the relationships among productive inputs, it would seem to be straining the metaphor to describe production as a function at all. It seems necessary, instead, to address directly the structural interrelationships among capital goods.

It Ignores Structural Elements of Complementarity and Indivisibility. Because it assumes that capital is homogeneous and unchanging except in quantity, mainstream theory does not address fundamentally important *structural* aspects of capital which have been elucidated by the Austrian School, especially Ludwig Lachmann. A realistic view of the process of capital accumulation and its effects must take into account several factors that the Harrod-Domar-Solow theory ignores.

The core point is that capital accumulation generally involves a lengthening of the capital structure, with what Lachmann calls a "'division of capital,' a specialization of individual capital items, which enables us to resist the law of diminishing returns" (1978:79). Capital accumulation is primarily manifested not in the addition of more of the same. It occurs in what we might call a "complexifying" of the capital structure, an increasing intricacy of the pattern(s) of complementarity among increasingly specialized capital goods, born in the on-going growth and division of knowledge.[22] Capital accumulation "does not take the form of multiplication of existing items, but that of a change in the composition of capital combinations. Some items will not be increased at all while entirely new ones will appear on the stage" (Lachmann 1978:79). The homogeneity assumption obscures this key fact.

In pointing to "capital combinations," Lachmann stresses *complementarity* in this kind of process, and indivisibility of capital goods that is usually involved. Generally the various items in a new, more complex capital structure have no usefulness at all except in combination with the other items, and those items are indivisible. "It will not pay to install an indivisible capital good," says Lachmann, "unless there are enough complementary capital goods to justify it. Until the quantity of goods in transit has reached a certain size it does not pay to build a railway" (p. 80).

A consequence of complementarities in capital use is that new economies of scale become possible, or rather economical, as a result of capital accumulation. These economies are the consequence not of the size of particular production processes (the sense in which we usually think of scale economies), but of the scope of their interaction. It makes sense to invest in a large-scale, indivisible capital item only in the presence of the necessary complementary capital. Lachmann gives a strong illustration: "The accumulation of capital does not merely provide us with the means to build power stations, it also provides us with enough factories to make them pay and enough coal to make them work" (p. 80). The greater scale economies possible in the power stations and the factories depend for their economic feasibility on one another. Similarly, it is said that the spreadsheet program drove the initial explosion of personal computer sales: The tremendous economies that have been achieved in computer hardware over the last decade have been achieved through very large scale production, which itself has been driven by high-volume sales of popular software packages such as spreadsheets. On this view capital accumulation can affect growth in a way that is more exponential than geometric.

In *Growth Theory*, Robert Solow defines the stock of capital in his model as "the sum of past net investments" (1970:4), maintaining the idea that new capital is simply added onto old. But because complementarity is fundamental to capital—because capital goods must be used jointly with some specific others—old capital is often destroyed in the process of capital accumulation; that is, its value is destroyed in Schumpeterian "creative destruction." This is another basic fact of economic life that the Harrod-Domar-Solow approach ignores.

Millions of dollars worth of whaling equipment was destroyed by the growth of the kerosene industry; vast quantities of iron-producing capital was destroyed by the advent of the capital goods that produce steel; software applications are made obsolete every few months as better come along. In the regrouping process that Lachmann describes, "some of these capital goods will have to be shifted to other uses while others, which cannot be shifted, may lose their capital character altogether. Thus the accumulation of capital always destroys some capital" (Lachmann 1970:80).

Increasing returns to scale are also absent from the Harrod-Domar-Solow approach. Growing economies of scale are not inevitable in a free economy, but likely; they can and do result from the capital accumulation that occurs in practice. In Lachmann's terms,

> We conclude that the accumulation of capital renders possible a higher degree of the division of capital; that capital specialization as a rule takes the form of an increasing number of processing stages and a change in the composition of the raw material flow as well as of the capital combinations at each stage; that the changing pattern of this composition permits the use of new indivisible resources; that these indivisibilities account for increasing returns to capital. . . (p. 85).

Theorists such as Harrod and Solow, and even Paul Romer, whose work we take up below, assume a diminishing marginal productivity of capital. This assumption would make perfect sense if the kinds of capital being used did not change, but because they do change, it makes no sense at all. It makes sense neither in consideration of the economy as a whole, over time, nor, more obviously, in particular sectors of the economy such as microprocessor manufacturing, in which ongoing investment in superior capital equipment has increased productivity by orders of magnitude. Because the capital structure improves, there is a strong tendency to *increasing* marginal productivity of capital.

Again, while one can understand the desire of Harrod and his followers to simplify aspects of real world activity for convenience in their model, one must be wary of such simplifications as those made regarding capital. Simplifications which misrepresent and obscure do not aid understanding.

Shortfalls in the "New Growth Theory" of Paul M. Romer

In recent years, the theory of economic growth has been developed in what is known as the "new growth theory"; a major contributor to this literature is Paul M. Romer.[23] Romer brings up some of the issues with which we are concerned in this paper, and shows real insight into their importance.

Valuable Additional Insights. . .

While most growth theory has posited "given technology," or, where technological change is allowed at all, treated it as exogenous, recent work has dropped this assumption. Nelson and Winter (1982), for example, allow endogenous technological change into their evolutionary simulation model. Romer addresses endogenous technological change directly. Indeed, he entitles a recent paper "Endogenous Technological Change" (1990). Among the premises of his argument which constitute departures from old growth theory are "that technological change—improvement in the instructions for mixing together raw materials—lies at the heart of economic growth," and "that technological change arises in large part because of intentional actions taken by people who respond to market incentives."

Whereas Nelson and Winter retained the notion of homogeneous capital, Romer goes a step further, and explicitly includes heterogeneity of capital goods. "The unusual feature of the production technology assumed here," Romer says, "is that it disaggregates capital into an infinite number of distinct types of producer durables" (1990:S80).

Furthermore, Romer also brings out the link between knowledge and capital, ascribing the variety of capital goods to the different knowledge embodied in capital. He treats "long-run growth" as "driven primarily by the accumulation of knowledge by forward-looking, profit-maximizing agents," with a "focus on knowledge as the basic form of capital" (1986:1003). This knowledge is embodied in capital goods:

> The research sector uses human capital and the existing stock of knowledge to produce new knowledge. Specifically, it produces designs for new producer durables. An intermediate-goods sector uses the designs from the research sector together with forgone output to produce the large number of producer durables that are available for use in final-goods production at any time (1990:S79).

Additionally, Romer takes seriously increasing returns in production where knowledge is increasing. His 1986 paper, entitled "Increasing Returns and Long-Run Growth," gives a "view of long-run prospects for growth" in which "per capita output can grow without bound, possibly at a rate that is monotonically increasing over time. The rate of investment and the rate of return on capital may increase rather than decrease with increases in the capital stock" (p. 1003).

From this work, then, one might hope for some illumination about the relationship between capital goods and economic development.

. . . but Failure to Develop the Insights

These hopes are disappointed, however. Romer seems interested not so much in exploring the implications of his insights as with forcing them into the Procrustean bed of mathematical tractability. As a result, his treatment of capital and its role in production is still very meager. Indeed, his models take the life out of his introductory discussions.

Although Romer talks of and models technological change, the change he talks about is superficial. Consider the production function from the model in his 1990 paper:

> [A] simple functional form for output is the following extension of the Cobb-Douglas production function:
>
> $$Y(H_Y, L, x) = H_Y^a L^b \sum_{i=1}^{\infty} x_i^{1-a-b}$$

> This production function differs from the usual production function only in its assumption about the degree to which different types of capital goods are substitutes for each other. In the conventional specification, total capital K is implicitly defined as being proportional to the sum of all the different types of capital. This definition implies that all capital goods are perfect substitutes. One additional dollar of capital in the form of a truck has the same effect on the marginal productivity of mainframe computers as an additional dollar's worth of computers. [This equation] expresses output as an additively separable function of all the different types of capital goods so that one additional dollar of trucks has no effect on the marginal productivity of computers (p. S81).

Y here is "final output"; H_Y is "human capital devoted to final output," and the various capital goods are the indexed values x_i.

To treat "output as an additively separable function of all the different types of capital goods" is to treat capital as homogeneous again, notwithstanding Romer's efforts to consider "distinct types of producer durables." Defining his production function in this way allows Romer to add additional *types* of capital goods indefinitely, just as Harrod could add additional *numbers* of capital goods indefinitely. In both cases, only the magnitude of the capital variable changes, not the form of the function. Implicitly, then, capital goods are all of a kind in respect to *how they interact*. To a given capital structure, add buggy whips or microchips (for Harrod add new quantities; for Romer, add new designs) and the effect on output will be the same. Not only does "one additional dollar of trucks have no effect on the marginal productivity of computers," but also it has no effect on the marginal productivity of either the roads it complements or the railroad freight cars for which it substitutes. Capital is aggregable and thus implicitly homogeneous. Homogeneity of capital is further implied by Romer's construction of the production function as homogeneous of degree one (not so different from Solow after all). Where there are constant returns to scale, truly new and better production processes, which let us produce more with the same amount of input, are ruled out.

Lachmann's point that "[*c*]*omplementarity* is of the essence of capital use," (1978:3, emphasis in original) is just as damaging to Romer's actual formulation of his model as it is to the work of Harrod. Romer leaves no room for complementarity, nor its concomitant substitutability (and hence capital destruction). In brief, Romer leaves no room for any of the structural aspects of capital that are of fundamental importance to development. To illustrate briefly, consider the relationships among three elements of the software capital structure: the programming system Smalltalk, the programming language COBOL, and WindowBuilder, a set of tools for developing graphical user interfaces. WindowBuilder is built in Smalltalk, for use with Smalltalk—without Smalltalk present it cannot work. COBOL is an older programming language that is arguably being made obsolete by object-oriented languages such as Smalltalk.[24] How are we to make sense of "additive separability" in respect to these three? Not only are Smalltalk and WindowBuilder directly complementary, in the strict sense that one requires the other to be running on the same computer, but also WindowBuilder itself, having been built in Smalltalk, could never have come into being without Smalltalk. Suppose we "subtract" Smalltalk from the equation, what becomes of WindowBuilder?

Then it never was. These are not "additively separable." Furthermore, COBOL is being replaced by Smalltalk in certain cases. Then is the productive power of Smalltalk "added" to that of COBOL, or does it subtract from it?

Structural issues of complementarity and substitutability, as well as dependencies of one design on another, as of WindowBuilder on Smalltalk, are of fundamental importance in understanding how human well-being advances. We will find no help with these in the new growth theory. Romer says, "An investigation of complementarity as well as of mixtures of types of substitutability is left for future work" (1990:S81).

A main question we seek to answer is, "What is the nature of the process by which people learn how to fashion better tools?" Here again, Romer gives little help. Within his model of a three sector economy, he models technological innovation as occurring in a research sector. The research sector draws on available human capital and, making use of the current stock of technological knowledge, produces new technological knowledge in the form of designs for production goods. This new knowledge is then licensed to the production goods sector, which may build the designs into new and better capital equipment in subsequent periods. The new capital equipment is then utilized by the final goods sector to produce consumable output. His substantive description of the process by which people learn how to fashion better tools is as follows:

> It remains to specify the process for the accumulation of new designs, that is, for the growth of A*t*. As noted above, research output depends on the amount of human capital devoted to research. It also depends on the stock of knowledge available to a person doing research.

Romer continues,

> If designs were treated as discrete indivisible objects that are not produced by a deterministic production process, the production technology for designs would have to take explicit account of both integer constraints and uncertainty. There is no doubt that both indivisibility and uncertainty are important at the micro level and over short periods of time. The simplifying assumption made here is that neither is crucial to a first-pass analysis of technological change at the aggregate level (p. S82).

After presenting an adjusted formalization of the model, he continues, "With this formal structure, the output of new designs produced by researcher j can be written as a continuous, deterministic function of the inputs applied" (p. S83).

Given our purposes, this is disappointing. Having been urged so far in the paper to recognize the importance of technological progress, we may naturally ask of it, "what is the nature of the process?" If so, we must content ourselves with the answer that technological progress is "a continuous, deterministic function of the inputs applied," that is, human capital and the stock of knowledge. It amounts essentially to this: when well-trained researchers are given a lot of good information, they think up new technologies.

The new growth theory has little to say about the *process* by which technological progress occurs. Indeed, it does not seem to be concerned with accounting for human economic advancement. Romer's paper does not; its attention is on requirements for and characteristics of a balanced growth equilibrium that is generated by its model. Because it is based in a general equilibrium framework, there is no room for process: there is no uncertainty, no real time, no need for adjustment, no capital destruction. None of the richness of a mutual adjustment process in conditions of uncertainty is to be found here. The manner in which Romer formalizes his discussion takes the richness out of it, leaving it in the end little better, for understanding the process of economic development, than the traditional models.

Like Harrod and Solow, Romer neglects the structural elements of capital. He chooses to ignore that the growth and division of knowledge lead to a growing complexity of complementary relationships among capital goods. For Romer, introducing new knowledge into production is essentially a research effort, not a coordination challenge.

III. Implications for Growth Theory

In this final section we draw some conclusions about determinants of rates of economic growth, as suggested by our view of capital as knowledge and capital development as a social learning process. On the one hand, we can identify factors which tend toward an ever more rapid improvement in the capital structure and hence toward ever more rapid economic growth—speaking metaphorically, toward exponential growth. On the other hand, we can identify factors which offset, perhaps entirely, the tendencies toward ever-faster growth. These offsetting factors are quite different from those used to limit growth rates in traditional growth theory models. Rather they arise from the challenge of social learning.

Tendencies Toward Exponential Growth

Because economic development is in large part a matter of the “complexifying” of the capital structure—the on-going enrichment of the capital structure as new, ever more specialized knowledge is developed, embodied in intersubjectively useful form, and put to work in coordination with other capital in ever more lengthy and hence more productive systems of production—because this process is a learning process, and because we show signs of learning how to learn better,[25] an argument can be made that in the development of the capital structure there are tendencies toward increasingly rapid, or exponential growth.[26]

Recursion. One factor which seems to point in the direction of exponential growth is analogous to what computer programmers call recursion. Recursion is a function’s making use of itself, in a kind of a feedback, or perhaps more aptly, feed-forward process. This kind of feed-forward is commonplace in capital structure development. Consider that better steel makes possible better steel mills and better rails for transporting steel. With software, the recursion is often rapid and powerful.

There is, for example, a strong feed-forward dynamic between software and computer hardware. The design and manufacture of computer hardware is, of course, a demanding, complex matter. It is accordingly almost entirely computerized—under software control. But better computer hardware makes possible better computer software, in a never-ending loop. In the late 1980s and early ’90s, Texas Instruments developed a new generation of computer integrated manufacturing (CIM) systems for building computer chips. One of the decisions they made in choosing the programming language in which to build this system was to ignore hardware requirements—the system would be allowed to gobble as much memory and processing power as it needed; no functionality was to be sacrificed on that score. Despite the fact that Texas Instruments manufactures hardware, this sort of decision could not have been made too many years ago: processing power was too expensive. But hardware costs have dropped. Given a free hand with system size, the Texas Instruments engineers were free to choose the best available software development system, with which to build the best possible software. They chose Smalltalk and a number of related tools for the Smalltalk environment, and produced therewith a remarkable computer integrated manufacturing system, said to improve throughput by a factor of 100 over the best previous methods. But notably, this system is primarily used to produce . . . computer hardware. This better, cheaper hardware may of course be used in the future to enable still more ambitious software systems . . . and so the loop will surely continue.

General Computerization. In the economy as a whole, the effects of computerization are very significant. The benefits of computation are being extended into virtually every area of human endeavor, making possible great precision, capture of information, widespread, inexpensive communication, and a host of tools and processes that were impossible before. Consider, for example, new tools for rapid prototyping of machine parts. Software is used in producing drawings (this is computer-aided design), in sending the drawings electronically to a prototyping device that hardens of layers of polymer with lasers, in directing the lasers that harden the polymer, and in precisely lowering the platform on which the model takes shape, layer by layer. As the software for these purposes is improved, tool prototyping will improve. Through such prototyping and other kinds of simulation it enables, better software will improve the speed and quality of production of virtually every hard good we use.

Learning to Use Software. Beyond the simple improvement of current processes through computer use is the development of new processes that computers and software make possible. This latter effect of software on capital structure development will be the more profound. Up to the present we have mostly used computers to automate old processes; we are just beginning to learn how to use them to do new and different things. Perhaps as significant, we are just beginning to learn how to adjust management techniques and organizational structures to complement the capabilities of computers.

We see this fact in the production of software itself: A great deal of work is being done on learning to manage the software production process better, to take advantage of reuse of existing code, to facilitate team programming, and to develop families of products rather than a stream of individual projects. In manufacturing fields computers provide immediate availability of information on a process, and the ability to generate what-if scenarios through computer simulations. These are powerful resources that enable management to respond more quickly and intelligently to changing circumstances. Again, it will take us a while to learn how to use these tools well, but as we improve we can expect still further advances.

Significantly, in some areas of the economy at least, we seem to be learning how to enable better, more rapid learning at a number of levels. Clearly the software development community has recognized the importance of building evolvable systems that can “learn” effectively. A similar awareness seems to be growing in management circles. Wheelwright and Clark (1992), recommend management techniques that help manufacturers learn from experience; Peter Senge has coined the term, "the learning organization" (1990). To the extent that we do achieve significant social learning about how to learn better, how to improve our productive processes more rapidly, we have a tendency toward exponential growth. The quality of our tools and processes, and hence our productivity per person, would seem able *in principle* to spiral upward without limit, outrunning the growth of population, at an accelerating pace.[27]

Ever more rapid growth seems possible in principle. It would even be likely if the social learning that drives it were spread evenly throughout the economy in well-coordinated fashion, and if valuable knowledge embodied in new capital goods did not make some old capital goods obsolete. But of course the actual process is not so neat and simple.

Checks on Exponential Growth

Economists are properly uncomfortable with models that imply exponential growth. Even those unconcerned about the tractability of mathematical models point out that empirically, exponential growth does not seem to be occurring on an economy-wide basis.[28]

It seems that if there are tendencies toward exponential growth, they are checked in large measure by countervailing tendencies. Our contention is that the inescapable messiness of the social learning process itself puts up important checks on any tendencies toward exponential growth. These checks are quite different, however, from those posited in mainstream growth theory.

Checks to Growth in the "New Growth Theory". The new growth theory of Paul Romer takes seriously some of the knowledge issues we have considered. Romer's work focuses on "knowledge as the basic form of capital" (1986:1003), considers "endogenous technological change" (1990), and finds that "growth rates can be increasing over time" (1986:1002). With all this, we agree.

Where we differ with Romer is in our views on what factors slow these tendencies to increasing rates of growth. In the simple models used by Romer and other growth theorists, models which assume perfect knowledge and allow for no capital destruction, there are no obvious factors tending to slow growth. But without some such impeding factors, the models would have indeterminate solutions, would go to infinity. This result being unacceptable to these theorists, they build into their models a variety of ad hoc assumptions which make the models tractable, and result in some equilibrium growth path, or at least bounds on the possible rate of growth. Arrow limits the model in his learning-by-doing paper, for example, by assuming, in Romer's terms, "that the marginal product of capital is diminishing given a fixed supply of labor" (Romer 1986:1006). Others rely arbitrarily on upper bounds to the production function (Romer 1986:1007). Romer himself relies, in his 1986 paper, on "diminishing returns in the research technology" (p. 1006), and in his 1990 paper on the assumption that human capital "must ultimately approach an upper bound," given fixed population (p. S80).

Examination of the nature of capital, as well as empirical research in the history of software development in which this article originated (Baetjer, 1998), forces us to reject all of these restrictions. As capital is divided and improved, its marginal product can increase rather than decrease; the production function for any particular kind of good—its structure of production—can improve as knowledge grows and is embodied in new capital goods. Hence Arrow's diminishing marginal product of capital must be rejected. Romer separates the "research technology" by which new designs are created from production technology and asserts that research technology is subject to diminishing returns. In practice, however, new designs are actually developed to a great extent in the *production* of goods rather than in research as such.[29]

More importantly, the technological learning that he chooses to call research we have found to be a social learning process which itself can be improved: investment in new development tools and methodologies yield increasing returns in the quality of learning.

As for Romer's assertion that human capital "must ultimately approach an upper bound," given fixed population, it seems to confuse the amount of knowledge a given population can hold in their minds with the value, or productive power, of that knowledge. Certainly we are limited in how much we can know. But as the capital structure advances and improves, knowledge that at one time was held in people's minds as human capital becomes embodied in capital goods. From then on, it is no longer necessary for people to know it in a personal manner. The knowledge is now available intersubjectively in the capital structure. But that means there is now free space in people's minds for new personal knowledge, new human capital, appropriate to the capital structure in its new stage of evolution. Recall Thomas Sowell's observation that "the intellectual advantage of civilization . . . is not necessarily that each civilized man has more knowledge [than primitive savages], but that he *requires* far *less*" (1980:7, emphasis in original). Economic growth does not depend on people's knowing more and more, but on what they know evolving so as to complement the evolving capital structure in which they must function.[30]

The Check to Growth Evident Here: The Challenge of Social Learning. The present investigation suggests that in searching for factors that limit the rate of economic development, we must look elsewhere than to the kinds of limitations modeled in growth theory. In simple terms, what checks the tendency to ever more rapid economic development is that learning is challenging, time consuming, and local. If there were perfect information, if learning were easy, if new knowledge could be costlessly embodied in new capital goods, and if insights gained spread immediately and costlessly throughout the whole economic system, then growth rates would be infinite. But in fact the learning process on which economic development depends is costly in time and effort, because it is iterative and dialogical—it goes forward by a kind of conversation in which people with different, frequently tacit knowledge, must somehow blend their particular knowledge contributions into a new capital good.[31]

This process is so challenging that many individuals and organizations don't manage it at all. The learning which does occur is distributed widely throughout the capital structure in various people and tool systems. New learning occurs in different parts of that structure at different times, and it takes time for relevant knowledge once gained to spread (i.e., be learned by others, or sold to others embodied in capital goods). Social learning is also coevolutionary: it involves complex complementarities that shift in time, and of course there is no guarantee that good coordination will be maintained as different parts of the overall system progress at different rates and in sometimes conflicting directions.

As a result of these characteristics, economic development in any branch of the economy frequently destroys some capital and makes other more valuable. Hence the process is not cumulative; new learning and new capital cannot always be added to old. Economic development is indeterminate and path dependent: there is no equilibrium toward which it tends; there are myriad possible paths along which it can proceed. Sometimes progress in one area is reinforced by complementary progress in another; sometimes what might have been progress in one area turns out to be a total waste, because necessary complements are not developed. Accordingly, the process is uncertain. It requires constant readjustment of plans, constant new learning, new efforts to establish or maintain a useful place in the structure of production. While in one sector of the economy social learning may be hurtling forward, and production there enjoying increasing returns to investment, that very progress may be rendering whole other sectors obsolete, destroying the value of the knowledge embodied there, and sending software, equipment, and whole classes of human capital to the scrap heap, literally or figuratively.

What checks economic growth rates, what restrains economic development from the unrestrained advance toward which it tends, is that learning is difficult. It is uncertain, time-consuming, and local. At present, at least, we do not seem to be very good at it. While there seem to be no inherent obstacles to exponential growth, it is certainly difficult to achieve. There is no fundamental tendency to diminishing marginal utility of capital, for example, nor fundamental limits to the value of the human capital we can develop in society. Rather, for the myriad different elements of an unfathomably complex structure of production to coevolve rapidly, while maintaining a high degree of complementarity, is difficult.

Notes

1. This view of human advancement I derive from the Austrian School of economics and in particular from the founder of the Austrian School, Carl Menger. Essential works in this tradition are Menger (1981), Bohm-Bawerk (1959), Hayek (1935 and 1941), Mises (1966), and Lachmann (1978).
2. Consumption goods also have a knowledge aspect, of course. Indeed, knowledge is a necessary aspect of any economic good, if by economic good we mean something people value. It is only because of our knowledge that something will satisfy some purpose—in either consumption or production—that we consider it a good. Hence we may reasonably say that consumption goods are embodied knowledge also: they embody knowledge of what will directly satisfy our wants.
3. Hayek writes,

> Take the concept of a ‘tool’ or ‘instrument,’ or of any particular tool such as a hammer or a barometer. It is easily seen that these concepts cannot be interpreted to refer to ‘objective facts,’ that is, to things irrespective of what people think about them. Careful logical analysis of these concepts will show that they all express relationships between several (at least three) terms, of which one is the acting or thinking person, the second some desired or imagined effect, and the third a thing in the ordinary sense. If the reader will attempt a definition he will soon find that he cannot give one without using some term such as ‘suitable for’ or ‘intended for’ or some other expression referring to the use for which it is designed by somebody. And a definition which is to comprise all instances of the class will not contain any reference to its substance, or shape, or other physical attribute. An ordinary hammer and a steamhammer, or an aneroid barometer and a mercury barometer, have nothing in common except the purpose for which men think they can be used (1979:44).

4. Personal conversation with Robert Polutchko of Martin Marietta Corp.
5. (1981:74). See also Vaughn (1990).
6. Those others, of course, bringing to our words different experience and outlook, will understand what we say somewhat differently from the way we do.
7. Menger (1981). For a discussion of Menger's criticism, see Vaughn (1990).
8. ...which reaps scores of acres in hours, while its driver sits in air-conditioned comfort listening to Willie Nelson in stereo.
9. Lachmann credits Hayek (1935) with "reinterpreting the extended time dimension of capital as an increasing degree of complexity of the pattern of complementarity displayed by the capital structure" (1975:4).
10. See Mises (1949:93–4).
11. The very fact that there are orders of capital goods calls into question Paul Romer's assumption that new capital goods have an additively separable effect on output. (See below.) Lower order goods always depend on the higher order goods that produce them; goods related this way cannot be separable in their effects.
12. Indeed, product design in manufacturing industries is receiving a lot of attention. See Wheelwright and Clark (1992), and Womack et. al. (1990).
13. Womack et al. (1990:104–6).
14. Again, we must think of the design of the new good—the model of tractor or version of a software application—rather than any particular instance.
15. Harrod (1939:18). All references to Harrod are from this work.
16. Solow (1959:9). Unless otherwise noted, all references to Solow are from this work.
17. An economy's aggregate capital stock cannot be measured, although a firm's can be, in a loose sense: based on estimates of future income streams, a firm can calculate the money value of its capital. Economic calculation achieves a rough and ready way of measuring the value of capital for a given profit center.
18. Joan Robinson, *The Rate of Interest*, *and other Essays*, p. 54, quoted in Lachmann (1978), p. 5.
19. See also Hayek (1935) and Lachmann (1975 and 1986).
20. Harrod's 1939 article, "An Essay in Dynamic Theory" entails the following elements:

G	the geometric rate of growth of output or income
Gw	the "warranted" rate of growth
$x0$, $x1$	output, periods 0 and 1
s	the savings rate as a fraction of income
C	the "capital coefficient," "the value of the capital goods required for the production of a unit increment in output"
Cp	the actual capital coefficient; "the value of the increment of capital per unit increment of output actually produced"

While G is simply the growth rate that actually occurs, Gw, the warranted rate "is taken to be that rate of growth which, if it occurs, will leave all parties satisfied that they have produced neither more nor less than the right amount. ...it will put them into a frame of mind which will cause them to give such orders as will maintain the same rate of growth."

The model that Harrod puts together from these concepts depends on two closely related equations. His "Fundamental Equation" is $\text{Gw} = s/C$. This gives the warranted rate. The formula for the actual rate of growth is $G = s/\text{Cp}$. The whole theory turns on divergences between these two.

21. This is true unless "the capital stock" can be "constant" even while the composition of that capital stock (to use a term Solow does not) changes. Solow suggests such a possibility:

> It should be realized that this reduction of technological progress to the efficiency-unit content of an hour of labour is a metaphor. It need not refer to any change in the intrinsic quality of labour itself. It could in fact be an improvement in the design of the typewriter that gives one secretary the strength of 1.04 secretaries after a year has gone by. What matters is this special property that there should be a way of calculating efficiency-units of labour, dependent on the passage of time but not on the stock of capital, so that the input-output curve doesn't change at all in that system of measurement (p. 35).

The passage implies that improvements in capital can occur (e.g., the better typewriter) independent of a change "in the stock of capital." Surely this conception presents difficulties in how we measure the stock of capital, and invites the question of why technology which yields a better typewriter design is not "capital-augmenting."

22. Lachmann, following Hayek (1935), holds that over time there develops "an increasing degree of complexity of the pattern of complementarity displayed by the capital structure" (1975:201).
23. Other important contributions include Lucas (1988) and Arrow (1962). For useful surveys of relevant work, see Buchanan and Yoon (1994). Also see Diamond (1990), especially Dixit (1990) and Stiglitz (1990).
24. The problems many businesses experienced with reprogramming their old COBOL programs to deal with the year 2000 illustrates one reason *why* it is obsolete.
25. Some people are even working on learning how to learn how to learn. See the work of Doug Englebart on augmentation of knowledge (1963).
26. Arguably some parts of the world are experiencing exponential growth even now. In the long perspective of human history, certainly the pace of change seems to be accelerating. If we do not see present growth as exponential, perhaps that is because we are still so far down on the curve that it still looks flat.
27. For a persuasive presentation of a possible, indeed likely, technological basis for a marked upturn in the curve of economic development, see Drexler (1986). The work of Drexler and others on the prospects of molecular manufacturing (nanotechnology) is available at www.foresight.com.
28. Of course it is possible that the perspective of more years may show that in fact growth rates are increasing, but that we can't tell because we are at such an early stage of economic development.
29. Consider, for example, Adam Smith's case of the boy who improved the steam engine. The boy was a worker on the spot, not a researcher. Being on the spot gave him practical insight into how to improve the machine's design.
30. Hayek has addressed this point. He quotes Alfred Whitehead as saying, "Civilization advances by extending the number of important operations which we can perform without thinking about them," and adds:

    > This is of profound significance in the social field. We made constant use of formulas, symbols, and rules whose meaning we do not understand and through the use of which we avail ourselves of the assistance of knowledge which individually we do not possess (1945:88).

31. See Baetjer (1998), especially Chapter 3, "Designing New Software Capital."

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