WORKING PAPERS

EAST-WEST CENTER WORKING PAPERS

EAST-WEST CENTER

The U.S. Congress established the East-West Center in 1960 to foster mutual understanding and cooperation among the governments and peoples of the Asia Pacific region including the United States. Funding for the Center comes from the U.S. government with additional support provided by private agencies, individuals, corporations, and Asian and Pacific governments.

East-West Center Working Papers are circulated for comment and to inform interested colleagues about work in progress at the Center.

For more information about the Center or to order publications, contact:

Publication Sales Office
East-West Center
1601 East-West Road
Honolulu, Hawaii 96848-1601

Telephone: 808-944-7145
Facsimile: 808-944-7376
Email: ewcbooks@EastWestCenter.org
Website: www.EastWestCenter.org

EAST-WEST CENTER WORKING PAPERS

EAST-WEST CENTER

Economics Series

No. 13, February 2001

Understanding Technological Change

Richard G. Lipsey

Richard G. Lipsey is an Emeritus Professor at the Simon Fraser University at Harbour Centre and Fellow of the Canadian Institute for Advanced Research, Canada.

This paper was presented at the international conference on "The Internet, Global Production Networks and Knowledge Diffusion" at the East-West Center, Honolulu, Hawaii, January 11–13, 2001.

Understanding Technological Change[1]

The purpose of this paper is to provide a background perspective for the applied papers at the conference. This perspective differs from that of neoclassical theory and is rooted in detailed micro studies by such students of technological change as Nathan Rosenberg and Christopher Freeman, as well as the theoretical structures based on evolutionary rather than equilibrium modeling. My colleagues and I call our own version of this branch of economics “structuralist-evolutionary”.[2]

Part I gives some background material on technology and technological change. Part II introduces the structuralist-evolutionary model and contrasts it with the neoclassical model of economic growth. Part III introduces the concept of a general purpose technology. Part IV discusses the current revolution in information and communications technology (ICTs) of which the internet is part. It concludes with a discussion of two important questions: “Is there a real ICT revolution or just a modest set of undramatic changes?” and what does total factor productivity actually measure?” Here I argue that TFP does not measure technological change and that its common use to evaluate the importance of the ICT revolution is misguided. Part V concludes with a few policy implications.

I. THE TECHNOLOGICAL BACKGROUND

A. Long-Term Growth Driven by Technological Change

Although technology is distrusted by many observers, humans are fundamentally technological animals. Indeed, technology is as old as the first hominid creatures, taking early forms in weapons, tools, clothing, methods of preparing food and the control of fire. Modern archaeological research suggests that, from the very outset of human evolution, technology has played a critical role.

---

[1] Virtually all of the original ideas expounded here are contained in a series of articles written over the past decade, many of which were co-authored with either or both Clifford Bekar and Kenneth Carlaw. My debt to both of these researchers, who were originally my graduate research students and research assistants, but are now university professors, will be obvious from the references throughout. I am also indebted to the conference participants for many helpful comments and criticisms.

[2] The original inspiration for our model was the concept of a techno-economic paradigm as expounded in Freeman and Perez (1988). Our reasons for not continuing to use their very insightful way of looking at major technological changes are given in Lipsey and Bekar (1995).

> **Technology is probably the most significant element in determining what we are today, not just in forming modern "civilization," but in directing the course of our evolution from a distant apelike ancestor....Genetically, anatomically, behaviorally, and socially, we have been shaped through natural selection into tool makers and tool users. This is the net result of more than .5 million years of evolutionary forces working on our biology and behavior…[which produced] human beings as profoundly technological creatures. (Schick and Toth 1993, 17–18.)**

Technology helped to turn us from apes into humans and then altered our behavior from animal-like hunting and gathering to members of complex and sophisticated civilizations.[3]

Long-term growth is driven by technological change—that is, by changes in the goods and services that we produce and in the way that we produce them. These changes imply that most calculations of the growth in real incomes are radical understatements of the full impact of economic growth on the average person.

> **Although we have five times as much market value of consumption as did our Victorian ancestors, we consume it largely in terms of *new commodities* made with *new techniques* that were unknown to the Victorians. They could not have imagined modern dental and medical equipment, penicillin, painkillers, bypass operations, safe births, personal computers, compact discs, television sets, automobiles, opportunities for cheap, fast, worldwide travel, affordable universities, safe food of great variety, or central heating, much less the elimination of endless kitchen drudgery through the use of detergents, washing machines, electric stoves, vacuum cleaners, and a host of other new household products that their great grandchildren take for granted. (Lipsey 1996:6)**

Nor could they have imagined today's clean, quiet, computer-assisted factory, largely run by robots and a host of other radically new methods of producing our goods and services and organizing our productive activities. *The point is important*. Technological advance not only raises our incomes; it transforms our lives by creating new, hitherto undreamed of things (new product technologies) and allowing us to make them in new, hitherto

---

[3] Presented with a problem, our technological nature makes us inclined to innovate our way out of it. So my co-authors and I take technological change as the rule in any society where conditions are changing. Thus, the historical problem is to explain why in some places and at some times technologies stagnated rather than to explain why in other places and at other times technological change was the rule (albeit at a pace that is slow by today's standards).

undreamed of ways (new process technologies).[4] In the long term, new technologies transform peoples' standards of living, their economic, social, and political ways of life, and even their value systems.

B. Growth Accumulation and Technological Change

Economic historians and students of technology agree that technological change is the major determinant of long-term, global economic growth.[5] However, virtually all new process technologies are embodied in new capital equipment, while virtually all new goods require new (or modified) capital goods to produce them. So investment and the savings that finance it are complementary with technological change. Anything that slows the rate of embodiment of new technologies through investment, such as unnecessarily high interest rates, will slow the rate of growth, just as any slowdown in the development of new technology will do so in the long term.

Surprisingly perhaps, growth is affected more in the short term by variations in investment then by variations in the rate of technological change. This is because there is always a large pool of existing technologies have not been fully exploited. Variations in the rate of investment cause variations in the rate of exploitation of these technologies. Nonetheless, as the argument in footnote 5 suggests, in the very long run it is technological change that has most influence on living standards—although the strong short run relation between growth and investment has erroneously led some observers to conclude that investment is the major determinate of long term growth and that technological change is relatively unimportant.

---

[4] Accepting the overwhelming importance of technological change in determining long-term economic growth does not imply economic determinism that makes technology sufficient to determine all social and economic outcomes. The same technology introduced into different social and economic structures typically produces very different results (which would not be the case if technology determined everything). The vastly different effects of TV on political processes in the US and the UK is one dramatic case in point.

[5] A simple thought experiment should make this point. Imagine freezing technological knowledge at the levels existing in, say, 1900, while continuing to accumulate more 1900-vintage machines and factories and using them to produce more 1900-vintage goods and services and while training more people longer and more thoroughly in the technological knowledge that was available in 1900. It is obvious that today we would have vastly lower living standards than we now enjoy (and pollution would be a massive problem).

C. Empirical Generalizations Concerning Technological Change

Here are some of the key empirical generalizations that are critical for understanding the behavior of technological change and evaluating innovation policies. These have been established through decades of research by students of technology.[6] Many are in clear contradiction to the assumptions commonly used in neoclassical economics and so provide a cautionary lesson concerning the dangers of using neoclassical theory to analyze technological change. For many micro-economic problems neoclassical comparative static analysis, with its assumptions of constant tastes and technology and stable equilibria, is extremely useful. But that theory is not well adapted to the study of micro-economic behavior in which technology is changing endogenously at a rate sufficiently fast to affect the outcome of the analysis. Other theories are needed to study such behavior.

1. Endogenous R&D

Because R&D is an expensive activity that is often undertaken by firms in search of profit, innovation is to a great extent endogenous to the economic system, altering in response to changes in perceived profit opportunities. Furthermore, pure science undertaken in such places as government and university laboratories is also largely endogenous. The reasons for this are more subtle than for the case of commercially directed R&D. (See Rosenberg, 1982, Chapter 7.) In the past, technological change has often led pure science by presenting it with the problem of understanding why certain practical technologies worked. Beginning in the later 19th century, however, science has more and more to lead technology in many areas (but by no means everywhere).

In contrast to the emphasis on short run price-quantity and long run capacity decisions found in most theoretical treatments of firms and industries, endogenous innovation is a major strategic variable for firms competing in manufacturing and service production.[7] Constant successful innovation is needed just to maintain one's market share. Ceteris paribus, a market served by a few competing oligopolists usually produces more

---

[6] Every one of these generalizations requires a least a chapter if not a book length treatment to do it justice.

[7] To handle this behavior, the Austrian concept of competition as a process is needed, rather than the neoclassical concept of competition as an end-state. In process competition: "...firms jostle for advantage by price and non-price competition, undercutting and outbidding rivals in the market-place by advertising outlays and promotional expenses, launching new differentiated products, new technical processes, new methods of marketing and new organizational forms, and even new reward structures for their employees, all for the sake of head-start profits that they know will soon be eroded. ...[in short] competition is an active process." (Blaug, 1977: 255-6)

innovation than either a market served by a monopolist or one served by price-taking firms whose revenue just cover their full costs of production. One reason why continual innovation is important to firms is that many inventions are not appropriable. Patents are easily circumvented except with a few products such as pharmaceuticals, chemicals, and the entities created by biotechnology.

Because technological competition takes place within an existing structure—institutions, methods of organization, and the location and nature of physical and human capital—there is no pure long run in which decisions take place in an environment unconstrained by the past decisions of any agent. Hence, neoclassical long run equilibrium theory is not only inapplicable, it is often misleading. Because what a firm or industry can do today is influenced by its acquired skills and experience, which are partly determined by what it did in the past, decisions about future developments are influenced by past decisions. For these, and many other reasons, technological change is path dependant.

Salients are one manifestation of path dependency. When a product or process is evolving, technical problems tend to be solved one at a time, seldom leaving the overall technology perfectly balanced. For instance, the wing of one type of aircraft may be currently able to bear more load than the engines can pull. This creates an incentive to improve the engines. The improved engines may then be able to do things that the current wings cannot support. In this way, technological change often evolves through a series of bottlenecks in which the alteration of one creates another.

2. Evolution of new technologies

Changes in both product and process technologies occur continuously and cover the whole range from incremental improvements in existing technologies to those that are revolutionary in conception and effect. A high proportion of all technical change takes the form of incremental changes to existing product and process technologies. The source of innovative ideas is sometimes found among up-stream suppliers, sometimes among producers, and sometimes among downstream users. How the location of these ideas differs across different industries can often be explained by the type of firm that can most easily appropriate the rents from innovation (von Hipple 1988).

Major radical innovations never bring new technologies into the world in fully developed form. Instead, these technologies typically first appear in a crude embryonic state with only a few specific uses. Improvements and diffusion then occur simultaneously as the technology is made more efficient and adapted for use over an increasingly wide range of applications. As a result, most development expenditure is on product not process development.

The diffusion of knowledge about successful innovations is a slow and costly business. Just to discover what is currently in use throughout the world is a daunting task, particularly for small firms. At best knowing what is done elsewhere only provides the blueprint; making it operational requires acquiring all the tacit knowledge that is required to operate any technology successfully. It follows that the existing set of technologies does not provide a freely available pool of knowledge available to all existing firms—many economic theories of growth notwithstanding. Instead learning about what is in use elsewhere and adapting it to one's own uses is a slow and costly process that typically requires innovation in its own right. (Thus, innovation and diffusion shade into each other rather than being fully distinct activities.)

Major innovations in product technologies, such as the introduction of wholly new products, often require only incremental changes in production technologies. Thus, in a process that Rosenberg (1976) calls technological convergence, technologies that produce such widely separated products as sewing machines, bicycles and automobiles shared common production technologies. It follows that cases in which radical innovations occur in both products and their production processes are much less common than one would think by studying products only. Furthermore, regional competitive advantages that persist through successive generations of new and often radically different product technologies are often based on process technologies that are common to these products (e.g., New England's long-term competitive advantage in guns, sewing machines, machine tools, and many other non-electronic manufactured products).

3. Technological spillovers

Innovations are vertically and horizontally linked to other innovations, often occurring in a related cluster of changes in several branches of the economy. The total set of these innovations produces much more additional value than the value that would be produced if each were introduced in isolation. Really major innovations affect the value of capital goods and production facilities as well as research programs throughout the economy, bringing gains and losses that do not affect the cost or profits of the original innovators. The importance of this point is inversely related to the time it takes to make it![8]

4. Uncertainty

Because innovation means doing something not done before, there is an element of uncertainty (in Frank Knight's sense of the term) in all innovation. It is often impossible even to enumerate in advance the possible outcomes of a particular line of research. Time and money are often spent investigating specific avenues of research to discover if they are blind alleys or full of immensely rich pots of gold. As a result, large sums are sometimes spent with no positive results, while trivial expenditures sometimes produce results of great value. Furthermore, the search for one objective often produces results of value for quite different objectives. All this implies that agents are making choices under conditions of uncertainty (in Frank Knight's sense of the term). They are not be able to assign probabilities to different occurrences in order to conduct risk analysis as conventionally defined.

---

[8] Technological complementarities, which are what lie behind technological spillovers and which are what allow growth based on technological change to persist indefinitely, are a much wider concept than the technological externalities that are usually viewed as the measure of technological spillovers. For elaboration see Lipsey and Carlaw (2000).

Uncertainty is involved in more than just making some initial technological breakthrough. There is uncertainty with respect to the range of applications that some new technology may have. The steam engine, electricity, the telephone, radio, the laser, the computer, the VCR, and fiber optics are examples of technologies that were initially thought to have very limited potential, and that did have very limited actual applications during the first decades of their lives. One other interesting case in point is that the internet was initially expected to be of most use in communications between producers and customers whereas communications among producers evolved to be more important.

Large technological leaps require more changes in the products, processes and supporting structures and hence, involve a greater exposure to uncertainty than do attempts at small technological changes. Commercialization is another important part of the innovative process that involves uncertainty. Many marvelous technological advances were commercial flops. A country that successfully commercializes fundamental developments made elsewhere can have an excellent growth record, while a country that makes fundamental developments that its domestic firms are unable to commercialize will have a poor growth record.

Because firms are making R&D choices under uncertainty, there is no unique line of behavior that maximizes their expected profits—if there were, all equally well-informed competing firms would be seeking the same breakthrough made in the same way. Because of the absence of a unique best line of behavior, firms should be visualized as groping into an uncertain future in a purposeful and profit-seeking manner (instead of maximizing the expected value of future profits).[9] The absence of maximization implies the absence of a unique optimum allocation of resources. The absence of an optimal allocation in turn implies that policy analysis based on removing impediments to achieving this optimum (standard piecemeal welfare analysis) is inapplicable. The profound effects for policy of this conclusion are briefly studies in Section V.[10]

Because of the fundamental uncertainties, competition in innovation cannot be guaranteed to select the best technology. For reasons analyzed by Arthur (1988), absorbing barriers, lock-in effects, and first-in or first-success advantages can easily arise. Because the losing technology is never developed to its full extent, we often never know what its full potential was.

[9] This approach to the behavior of firms has a long lineage going back at least to the work of Herbert Simon. Later it was pioneered in relation to growth and technical change in the seminal book by Richard Nelson and Sidney Winter (1982).

[10] I have studied these policy implications in a series of articles, many of which are co-authored with Kenneth Carlaw. See for example (2000) and the references therein. [RG L FN]

5. Scale effects

New technologies are often accompanied by reductions in unit costs of production associated with an increase in the scale of output. These are not scale effects as defined in economic theory and have nothing to do with indivisibilities. Instead, they are inherent in the three-dimensional geometry, the physics and the chemistry of the natural world. Technological improvements often allow these scale effects to be further exploited by permitting an increased scale of output. For example, the heat loss in a smelter is proportional to the area of its surface, while the amount that can be smelted is proportional to the volume of the smelter. Thus, there are cost economies in building larger smelters. But smelter size is limited by the available technology. In the 19th century, the development of better pumps to force air into smelters permitted an increase in the size of smelter thus lowering costs. Many similar examples exist and these help to account for the common observation of a technology that allows an increase in the scale of operations being accompanied by a fall in costs—but not for the reason envisaged in the abstract theory of scale effects. (This point is elaborated in Lipsey 2001.)

II. TWO VIEWS OF GROWTH AND TECHNOLOGICAL CHANGE [11]

To discuss technological change and economic dynamism, we need a theoretical model to act as a framework. The standard neo-classical model, which is shown in the first part of Figure 1, shows inputs passing through a macro-production function to produce the nation's output, as measured by its gross domestic product (GDP). (Figure 1 is at the end of the paper.) Institutions, and all other structural components, are hidden in the "black box" of the aggregate production function, having helped to determine the function's form. Technological change is only observable in this model by its effects on productivity (as measured by such variables as total factor productivity, TFP, or labor productivity, Y/L). So there is no way in which changes in technology and in productivity can be independently observed. For example, the model does not allow us to observe the coexistence of rapid technological change and slow productivity growth. It is the non-separation of those two phenomena that gives rise to productivity puzzles in periods when independent evidence suggests that technology is changing rapidly but productivity is changing only slowly or not at all. To discover the circumstances in which rapid technological change will or will not be accompanied by rapid productivity growth, we cannot employ a model that equates technological change with productivity growth.

[11] This section is based on a Chapter in Lipsey, Bekar and Carlaw (in preparation). The model that follows is not intended as a full description of the economy. All we need at this point is a fuller description than is provided by the neoclassical aggregate production function. In our book now in preparation, we distinguish technological and scientific knowledge and allow for social and other structures that are not included in our facilitating structure.

Our formulation is designed to separate changes in technology from changes in productivity and to reveal some of the elements of the neoclassical black box that research shows to be important for economic growth. Because this model makes the economy's *structure* explicit, and is also in line with much micro economic research on the *evolution* of technology, we call it a "structuralist-evolutionary" ("S-E") model. Since it breaks open the black box, we call it an "S-E decomposition".

A. Overview

In ordinary parlance, the term technology is used rather loosely to refer both to specifications, designs and blue prints on the one hand and their embodiment in specific items of capital equipment on the other. Neoclassical growth theory also does not distinguish these concepts.

In contrast, we make a sharp distinction between technological knowledge on the one hand and its embodiment in specific items and organizations on the other. Thus, our theory separates technological knowledge from the capital goods that embody much of it, making the latter a part of what we call the economy's "facilitating structure." The model also separately specifies public policies and the policy structures designed to give them effect.

B. Definitions

The six main categories in this model are shown in the second part of Figure 1.

Technological knowledge: This is the idea set of everything that can create economic value. The classes of technological knowledge are: p*roduct technologies*, which are the specifications of the products that can be produced, where products refer to both intermediate and final goods as well as services; p*rocess technologies*, which are the specifications of the processes that are, or currently could be, employed to produce these goods and services; o*rganizational technologies*, which are the specifications of how such value-creating activities as R&D, production, management, distribution and marketing, are organized.[12] Notice that our concept of technology is wider than the definition often used; it covers all codifiable knowledge of how to create all forms of economic value. (Tacit knowledge is part of human capital and hence a part of the facilitating structure.)[13] Where the meaning is clear, we use the term technology to refer to technological knowledge and/or its physical embodiment. Where the distinction between technological knowledge and its embodiment matters, we use separate terms.

---

[12] Product, process and organizational technologies include those directed at producing research results.

[13] Our intention is not to downgrade tacit knowledge as some readers have thought. Instead, it is merely to classify it where it belongs, as part embodied knowledge—in this case, knowledge embodied in people rather than in such inanimate things as capital goods and firm layouts.

The facilitating structure: We define the facilitating structure as the *realization set* of technological knowledge; it embodies that knowledge. To be useful, the great majority of technologies must be embodied in one way or another. The facilitating structure is comprised of the following:

- all physical capital,
- people and all human capital that resides in them, including tacit knowledge of how to operate existing value-creating facilities,
- the organization of production facilities, including labor practices,
- the managerial and financial organization of firms,
- the geographical location of firms and industries,
- industrial concentration,
- all infrastructure,
- all private-sector financial institutions, and financial instruments.

Inputs: For us, inputs are the basic materials that are transformed into outputs by the production process that is embedded in the facilitating structure. Our inputs are what the classical economists called "Land", which is physical land and all natural resources.[14]

---

[14] This definition of inputs raises the question: Why do we exclude the traditional inputs of capital and labor from our input set? Our answer with respect to capital is that it is a man-made factor of production, which embodies technological knowledge. The analysis of its place in the productive process and of its slow change in response to changing technological knowledge is best accomplished if we place it in the facilitating structure. As with all definitions, this is a matter of its usefulness, not of right or wrong. Our answer with respect to labor is that people are analytically similar to capital and, for consistency, we put them in the same category as physical capital. Theories often make the analytical distinction between pure "unskilled" labor and the human capital that is embodied in labor. But a genuinely unskilled person who embodied no learned human capital would be totally unemployable and hence of no economic value. From the time of birth, humans learn. They constantly acquire human capital and this knowledge is what makes them valuable as productive agents. So a laborer can be regarded in exactly the same way as capital. An item of physical capital is made of basic materials that have characteristics and that are formed into shapes that embody the technological knowledge without which the basic materials would be useless. Similarly, a newly born infant has characteristics. The grown worker has acquired a vast amount of human capital, without which he or she would be valueless. Thus, from our point of view, a laborer is as much a produced

"Land" is set apart from the other traditional "inputs" because the only truly exogenous inputs are those provided by nature. Agricultural land, forests, fish, all the natural materials, including ores and chemicals, are the basic materials. They are fed into the productive system that is embedded in the facilitating structure and are transformed by the services of capital and labor into outputs (what we call a performance variable).

Public policy: Public policy is the idea set covering the specification of the objectives of public policy as expressed in legislation, rules, regulations, procedures and precedents, as well as the specification of the means of achieving them, as expressed in the design and command structure of public sector institutions from the police force to government departments to international bodies. Public policy is made and changed by public sector agents such as legislatures and courts.

The policy structure: The policy structure is the realization set that provides the means of achieving public policies. It is embodied in public sector institutions and also includes the humans who staff these organizations and whose human capital embodies the knowledge related to the design and operation of public sector institutions, i.e., institutional competence. (Note the parallel with technology and its embodiment in capital goods which are a part of the facilitating structure.)

Economic performance: We refer to the system's economic performance rather than just its output since we wish to include more variables than just its GDP. Economic performance includes aggregate GDP, its growth rate, its breakdown among sectors, and among such broadly defined groupings as goods production and service production; aggregate GNP and its distribution among size and functional classes; total employment and unemployment and its distribution among such sub-groups as sectors and skill classes; "bads" such as pollution and other harmful environmental effects.

C. Behavior

1. Overview

At any particular time, the facilitating structure, in combination with primary inputs, produces economic performance. That structure is in turn influenced by technological knowledge and public policy. The introduction of any important new technology, or a radical improvement in an old technology, induces complex changes in the whole of the facilitating and policy structures. The full effects of any technical change on performance will not be felt until all the elements of the facilitating and policy structures have been

---

factor as is a piece of physical capital and each adjusts with lags when the needs of the productive process change.

adjusted to fit the newly embodied technology.[15] The performance of the economy at any moment in time is determined by, among other things, the compatibility of technology with those structures.

To study the behavior of our variables, we assume that all elements of the model are initially fully adjusted to the existing technologies. We then introduce a single exogenous change in one of the elements of the model and study the induced changes. This comparative static equilibrium analysis is used solely for purposes of understanding how the elements of the structure fit together. In practice, we expect the entire system to be evolving continuously, never reaching anything remotely resembling either a static equilibrium or a balanced growth path.

Starting from equilibrium, a change in technological knowledge will induce changes in the facilitating structure, in policy, and in performance. We take these in turn.

2. Adjustment of the facilitating structure

We mention just four of the important points that are related to the link between technology and structure.

First, if elements of technology change, various elements of the facilitating structure will need to change adaptively. For example, the technology of electricity generation had to be embodied in new electric motors, new generating stations (first using steam, then water power), new distribution networks and a host of other new types of capital. When electricity replaced steam to power factories the optimal size of plant increased, as did

[15] Some readers of earlier versions of this construction have complained that it was too "vague" for their liking. We finally discovered that "vague" meant that the variables could not all be measured on a numerical scale in the way that the inputs into the neoclassical production function can be defined as index numbers. We have two main responses. First, many of the variables that research shows to be important causes of technological change, such as the effectiveness of property rights protection, are not measurable as simple scalar values (at least with current measurement techniques). Second, the measured magnitudes used in neoclassical growth theory conceal some vagueness in their relations to the theoretical concepts that they purport to measure. What, for example, is meant by the concept of a given amount of pure capital when the capital is, in reality, a collection of heterogeneous goods? What does it mean to say that we have x% more of this pure capital than we had a century ago, although that real capital embodies very different technologies? It is all very well to say that the meaning is in the definition of the index number that we use to measure this concept, but if we cannot point to a real world counterpart of the concept of pure capital, we are involved in (possibly necessary) vagueness that our precise index number measures only conceal.

concentration in manufacturing industries. Geographic location was also altered because power could now be consumed in places widely dispersed from where it was generated. Human capital changed because machine operators required far less skill to handle the reliable electrically driven machines tools that replaced the less reliable steam driven machines.

Second, new technologies are typically first operated in a structure designed for their predecessors. (Consider electric motors in factories laid out for steam power, computers in offices organized around hard copy records, and early TV shows made in studios designed and staffed for radio.[16]) Thus, at any moment in time, the facilitating structure may be well or poorly adapted to any given state of technology. For example, labor practices with respect to job demarcation that were good adaptations to the Fordist production methods have not yet been fully adjusted to newer Toyotaist production methods.

Third, there are substantial inertias that resist change in most of the elements of the structure. Capital is often highly durable and will not be replaced by new capital embodying some superior technology as long as its variable costs of operation can be covered. The new pattern of industrial location and firm concentration will not be finalized until all the firms and plants are adjusted to the new technology. The optimal design of plant and management practices may not be obvious after the introduction of a new technology (as was the case with both steam and electricity). The understanding of what is needed by way of new infrastructure may take time, as will its design and construction (witness long Canadian discussion about the new information highway). New requirements for human capital must be established and the appropriate training devised (both on the job and in school).

Fourth, this period of adjustment is often "conflict ridden" (Freeman and Perez's term). First, old methods and organizations that worked well, often for decades, begin to function poorly in the new situation and often become dysfunctional. Second, the uncertainty accompanying any radical new innovations implies that there will be many different but defensible judgments of what adaptations are actually needed. Third, users may mistrust new technologies and/or take a long time to accept and adjust to them. Consider, for one dramatic example, the current conflicts associated with many of the aspects of biotechnology.

3. Adjustment of policy and the policy structure

Changes in technology and the facilitating structure typically require adaptations in policies and in the policy structures that are their instruments. For example, technological changes often turn natural monopolies into highly competitive industries (in the Austrian sense of the term as discussed in a previous footnote). The post office once had a natural monopoly in the delivery of hard copy messages but today that job can be done by courier, fax, e-mail, satellite link, and a host of other technologies, which have made this

---

[16] What this last trivial example shows is that at all levels of technology structure and newly introduced technologies are often incompatible.

activity highly competitive. A new technology can also do the reverse by introducing scale economies large enough for natural monopolies to emerge in what was previously an oligopolistic industry in which firms rigorously competed with each other.

Adjustments in policy and the policy structure tend to occur with long lags. Uncertainty about how the technology will evolve leaves agents unclear about what structural adjustments are required. This gives power to vested interests who wish to resist required changes. Inertias in political decision taking, plus the resistance of those who are hurt either by the new technologies, or by the accommodating changes in policy, can slow the process of adaptation. For example, decades after the ICT revolution made prohibitions on interstate banking obsolete, the US congress was still arguing over the revisions of the Glass Stegal Act that was passed in the wake of the 1929 stock market crash.[17]

3. Changes in performance

We have seen above that a change in technological knowledge requires a change in structure to make it operational, while the changes in structure often induce, or require, substantial changes in policies and the policy structure. Not only does new technology have to be embodied in new equipment, ancillary technologies need to be developed, and much of the facilitating structure needs to be redesigned to suit the new technology, which is initially operating in a structure adapted to the old. For these reasons, economic performance typically continues to change even after the new technology is in place because the facilitating and policy structures are still reacting and adapting to it. For example, it was decades after the introduction of electricity into factories before the technology completed its evolution. Electric motors first powered the single central drive that was typical of steam. They then powered several smaller drive shafts in the "group drive" that was an experiment in partial decentralization of the power system. Finally, the unit drive system put a separate engine on each machine tool. The flexibility of this arrangement then made possible a drastic alteration in the lay out of factories. Only after new factories with the new machines and new layouts replaced the long-lived steam driven ones was the full effects of electricity on industrial output and productivity felt, several decades after the first use of electricity in factories.

---

[17] Not only does policy need to react to changes in technology and in the facilitating structure, it may also be changed pro-actively in an attempt to alter technology or the structure. For example, a policy that directly subsidizes research on some new technology is operating directly on technology. A policy that encourages the establishment of R&D labs or richer links between the private sectors and universities is altering the facilitating structure in the expectation that these changes will influence the rate and nature of technological change.

D. Applications

One of the most important insights that follows from an S-E decomposition is that there are no necessary relations among the magnitudes of changes in technology, in the facilitating and policy structures, and in performance. Because changes in technology are only observable in neo-classical models by their effects on productivity (as measured by such variables as TFP or Y/L), many (probably most) economists assume that big changes in technology should be associated with big changes in productivity and are puzzled when they are not. But there is no reason to be puzzled. New technologies will replace older ones as long as they promise some gain in profitability. Sometimes the difference between the productivity of the old and the new is large and at other times it is small. Neoclassical observers often doubt the reality of major technological changes because productivity is not changing rapidly. But as the S-E decomposition emphasizes, there is no necessary relation between these variables. Current changes in productivity may or may not be well measured, but there is no paradox in there being major changes in technology with no accompanying rapid changes in measured productivity. This is what happened, for example, during the first phase of the Industrial Revolution when some of the new automated textile machinery was installed in sheds and driven by hand, while the rest was placed in small water-powered factories. A neoclassical observer would conclude that nothing important was happening to technology because TFP, Y/L, and real wages were not changing much. In fact, however, the technological basis for everything that happened later was being put in place, including transferring production from cottages to factories. To repeat the key point made earlier: *To study the circumstances under which rapid technological and structural change will and will not be accompanied by rapid productivity growth, we cannot employ a model that equates technological change with productivity growth.*

A second important insight that follows from our S-E theory is that there is no necessary relation between the magnitude of the change in technology and the changes it induces in the facilitating structure. Some important new technologies, including the laser, fit well into the existing facilitating structure and require few structural changes. Others, such as electricity and the computer, require massive changes in the facilitating and policy structures, changes that radically alter our way of life. What most observers see are the changes in the facilitating structure. These are then often confused with changes in technology. For example, when production moved out of the smaller proto-factories and into the great steam-driven factories in the early nineteenth century, this was a major change in the facilitating structure. Indeed, this was the stage of the Industrial Revolution when both the facilitating structure and performance changed most rapidly—the large industrial towns made their appearance while productivity and real wages finally began to rise steadily. Yet no new basic technologies were involved. All that happened was that the existing steam engines were combined with the existing automated textile machines. Many second order improvements were required in both technologies. But no great technological revolution was involved, for these had come earlier. *Nothing but confusion can result when technology, structure and performance are all changing in different ways and the events are interpreted by a theory that does not distinguish these.*

III. GENERAL PURPOSE TECHNOLOGIES

The overall technology systems of all growing economies evolve along paths that include both small incremental improvements and occasional jumps. To distinguish these, investigators often define two categories. An innovation is *incremental* if it is an improvement to an existing technology. An innovation is *radical* if it could not have evolved through incremental improvements in the technology that it displaces—e.g., artificial fabrics could not have evolved out of the natural fabrics that they displaced in many uses.

An extreme form of radical innovation is called a general purpose technology (GPT). GPTs share some important common characteristics: they begin as fairly crude technologies with a limited number of uses; they evolve into much more complex technologies with dramatic increases in the range of their use across the economy, and in the range of economic outputs that they help to produce. This evolution typically takes many decades, and can spread over a century. As mature technologies, they are widely used for a number of different purposes, and they have many complementarities in the sense of co-operating with many other technologies. A mature GPT is defined formally as a technology that is widely used, has many uses, and has many complementarities with other existing technologies.[18]

In our study of the history of technological change, we have identified about two dozen GPTs that have had really major impacts on the social and economic order, changing almost all aspects of society. They fall into five main categories, materials, energy, transportation, information & communication and organization. In chronological order, these are the domestication of crops, the domestication of animals, the wheel, the invention of writing, the invention of bronze, the introduction of iron, the water wheel, the three-masted sailing vessel, the steam engine, the factory system, the dynamo, easily manufactured steel, the internal combustion engine, the automobile, the airplane, mass production, the computer (and all of its derivatives such as the internet), lean production (Toyotaism) the laser, methods of creating new materials, biotechnology (just beginning to make its effects felt), and nanotechnology (in the future).[19]

A. Evolution of a GPT

A technology that eventually evolves into a GPT invariably starts in a relatively crude form with a limited number of uses (often one), and slowly develops the whole range of characteristics that we associate with a GPT. This initial evolutionary path is related to

---

[18] For a detailed consideration of these characteristics and a development of the definition that follows in the text see Lipsey, Bekar and Carlaw (1998a).

[19] I have discussed these past technologies in Lipsey and Bekar 1995 and Lipsey, Bekar and Carlaw 1988, and the upcoming ones in Lipsey 1999.

how agents learn about new technological ideas under conditions of uncertainty — learning by doing, learning by using, and by conscious experimentation.

As they evolve, GPTs interact with other technologies in many different ways. Even when a technology that eventually becomes a GPT is introduced to meet some specific crisis, as was steam to deal with water in ever-deepening English coal mines, it sooner or later begins to compete with technologies that are not themselves in crisis (e.g., sailing ships). Many of these older technologies are eventually overcome by the new technology, but only after a period of intense competition in which both technologies become more productive.

In other cases, the new technology will quickly become superior to the older competing technology. For example, when electric motors challenged steam in factories, they quickly established their supremacy as a power delivery system once the unit drive was established. Few new steam-driven factories were built thereafter (although existing steam-driven factories lasted for decades). In other cases, the initial margin of advantage is small and the transition correspondingly slow, as was the case when steam competed with water power in factories.

A new GPT often cooperates with an established technology that it eventually challenges. This was the case when early steam engines were sometimes used to lift water to help drive water wheels, and early airplanes delivered passengers to the ports used by transoceanic liners. When the new technology becomes dominant, it sometimes internalizes, or cooperates with, a revised version of the old technology. For example, the steam turbine, a combination of waterwheel and steam technologies, remains in use today as an electricity generating device.

In some cases, there may be little or no competition with the established technologies because the new technology fills a new niche. Regular, long-distance, trans-oceanic trade was created by the three masted sailing ship which had no established marine technology with which to compete over long distances. The internal combustion engine provided services which existing steam technologies could not—fast starting engines that were efficient at small horse power ratings and had relatively low weight/power ratios. Only when it was combined with electricity, did the hybrid diesel-electric engine seriously challenge steam on such major uses as ships and railways.

Sometimes a new GPT is complementary with a different type of existing technology. This was true, for example, of power and materials during the Industrial Revolution. Stronger materials were required before high pressure steam engines could be perfected.

In every case considered above, the full effect on productivity depends on the difference between the productivity of the new GPT and that of the technology it displaces. Since both technologies evolve, the effect is time dependant and cannot be predicted solely from a knowledge of the new GPT's own characteristics. [20]

Because, as already observed, the evolution of any technology is uncertain and hence difficult to predict, there is great variation in the stage of its evolution at which a new GPT is recognized as such. At one extreme, its potential may be recognized very early. This was the case with electricity. Ever since the invention of the voltaic cell in 1800, electricity was touted as an extremely important technology with massive potential. This was long before the invention of the dynamo in 1887 made electricity available in a form that could eventually fulfill its expectations. At the other extreme, a GPT may undergo decades of evolution before its revolutionary potential is recognized. For example, when computers were first commercialized after the Second World War, the civilian demand was estimated to be five. It took decades, and many ancillary innovations, before the computer was recognized as an all pervasive technology.

When (sooner or later) a GPT is actually perceived as an important new technology, it usually falls short of the expectations that are generated about its future development—in timing if not in eventual scope. This leads to a period of disillusionment followed by eventual surprise that the first expectations were correct. This uncertainty is often reflected in financial markets. Swings between optimism and pessimism cause major swings in share values and in company fortunes, of which the latest were being observed in late 2000 - early 2001. These swings could not happen if the evolution of new GPTs were not subject to high degrees of uncertainty.

B. Structural Adjustments

Every new GPT induces changes in the facilitating structure, although the extent and magnitude of these adjustments varies greatly from one GPT to another.

1. Long-term changes in structure

New physical capital: The evolution of a new GPT is accompanied by important changes in a wide range of technologies. Changes occur in both the internal makeup of stand-

[20] The points in this section are important qualification's to keep in mind when interpreting existing theoretical models of GPTs (see Helpman 1998). In these, all GPTs are treated the same; their effects are inherent in their internal structure; GPTs are instantly recognized as such at the moment of their discovery, their future evolution is then fully anticipated; only one GPT is assumed to be evolving at any point in time. The fact that modeling even so simple a version of a GPT is technically very difficult makes me pessimistic about the time it will take to develop more applicable models—or whether this will ever be done. It also shows how ridiculous is the commonly held view that if something cannot be formally modeled it is not economics.

alone capital goods, and in technology systems (grouping of stand-alone capital goods that cooperate with each other). Often the latter requires restructuring of the cooperating capital goods before the full potential of the technology system can be realized. A full explication of the rich experiences that fall into this category would require a paper in itself. (For more details see Lipsey, Bekar and Carlaw 1998b.)

Human capital: Required skills change with virtually every GPT. In British mines, the mule and horse handlers required much more skill than the drivers of the power-driven coal carriers that replaced them. Steam driven factories and machines required their machinists to be skilled in maintenance and repair, but the electric motor was more reliable so repair and maintenance was devolved to a few specialists.[21]

Reorganization of production facilities: A reorganization of the production process is usually required before the full potential of a new GPT can be realized. Early British textile factories were powered by animals, people, or water. The introduction of steam engines initially caused only a small increase in productivity. Large gains were not realized until the entire factory had been fully redesigned and its layout adapted to the power requirements of steam. Also, many ancillary innovations were needed before the full potential for speed and reliability of steam driven equipment could be realized.

Reorganization of management practices: New technologies often require new management structures. The early proto-factories of the First Industrial Revolution were small and typically owner managed. The large factories that followed the introduction of steam required a much more complex management structure and a new corporate form of finance to bring in a large number of non-managing investors.

Geographical relocation: New GPTs often alter optimal locational patterns. Water power restricted production to sites with reliable, fast-moving water flows. Although steam factories could be located anywhere, the cost of transporting coal was of major importance and power had to be used where it was generated. With electricity, the generation and use of power was separated spatially, freeing industry from the considerations of local power sources. Thus, the efficient geographical location of production facilities changed radically when steam replaced water, and when electricity replaced steam. The world still awaits the development of a widely applicable power source where the generation of the power can be separated *in time* from its use.

Industrial concentration: Different technologies have different inherent scale economies and these exert a major influence on industrial concentration. The use of water power required relatively small production units because the total horse power that any one site could generate was limited. Steam created large scale economies since the efficient size of a steam engine produced much more horse power than did the most efficient water wheel.

Changes in Infrastructure: New technologies typically require new infrastructure. For example, some of the most important cost components of early steam engine installations

---

[21] These observations provide a warning of the dangers of the assumption often made by growth theorists that the skill bias of successive new technologies always changes in the same direction.

were the sheds that housed the machine and coal, the foundational slab for the machine, and other micro-infrastructure requirements. Macro-infrastructure requirements included railway tracks, suitably designed ports, roads, and factories.

2. Transitional impacts on the facilitating structure

There are many reasons why the structural adjustments associated with the evolution of a new GPT are typically long-drawn-out and conflict-ridden. First, the required structural changes are subject to the same uncertainties as are the evolution of the GPT itself. The decisions that firms must take concerning the timing of the investment in new technologies, geographic relocations, size of firm (and hence industrial concentration) and internal financial structure, depend on many other structural adjustments. The uncertainty associated with the future evolutionary path of any new GPT implies that there is no *optimal* response in the facilitating (or the policy) structures at each point in time. Thus, rational agents in both the private and public sector may disagree about appropriate responses, even when all have the same information. Current debates about the restructuring of firms, labor practices, education systems and government policies with respect to science, technology, industry and regulation all reveal genuine differences in assessment about the best responses to new technologies—differences not solely motivated by the desire to protect special interests.

Second, many elements of the facilitating structure are characterized by large sunk costs which delay adjustment. This was one of the main reasons for the decades of delay in electrifying the whole manufacturing sector in North America and Europe. Also, many older workers find it difficult to retrain for the new technologies and the full adjustment may have to wait until the older generation is replaced by a new generation trained in the requirements of the new technologies.

Third, the required changes in the facilitating structure destroy many existing sources of rents and create many new ones. Those with vested interests in old sources of economic rent resist the changes. Since they often have substantial political power and long periods of conflict typically occur. For example, the Luddites, who were skilled craft persons, resisted the integration and mechanization of production that accompanied the Industrial Revolution in England. Similarly, many unions resisted the reorganization of work induced by the lean production methods of Toyotaism.

Fourth, some elements of structure do not respond easily because they are determined by non-economic forces such as custom, religion or public policy. The effects of a new technology on performance may be influenced by this unresponsiveness. For example, a public policy that resists the adjustment of the facilitating structure will result in a different economic performance than would occur if those adjustments were left wholly to the market.

3. Interactions with public policy and the policy structure

Changes in Public Policy: Technological changes and the resulting change in the facilitating structure often require major changes in policy. Natural monopolies are created and destroyed as one dominant technology supplants another. Competition policy needs to respond quickly to such changes. Property rights need to be defined over new technologies, as well as over their cooperating factors—e.g., streams that powered water wheels and airwaves for radio, TV and cellular phones, and genetic discoveries. New policies are required with respect to labor practices, competition and natural monopolies. Changes in the volume and nature of foreign trade and investment call for new forms of international cooperation and control. Covering these issues of public policy in any detail requires at least a paper. (See, for example, Lipsey 1997.)

Changes in the policy structure: Some changes are typically needed in the institutions that give effect to public policy. This is particularly apparent today, at the international level. ICT-assisted globalization is requiring international supervision of many issues involving trade and investment. The importance to most countries of a relatively free flow of international trade and investment has led them to transfer power over trade restrictions to supra national bodies such as the World Trade Organization, the EU, the NAFTA, and a host of other trade liberalizing institutions. The interrelation of trade and investment brought about by the ICT revolution has caused modern trade liberalizing agreements to be expanded to include measures to ensure the free flow and "national treatment" of foreign investment. The controversies over policies for globalization in general and the WTO in particular illustrate once again how these adjustments are so often conflict ridden.

IV. THE ICT REVOLUTION

The GPT revolution through which we are currently living is the revolution in Information and Communication Technologies (ICTs).[22] These are a cluster of new technologies centered around the computer but also including faxes, satellite transmissions, lasers and fiber optics (many of which were developed with the assistance of computers).

When computers were initially introduced, they entered structures designed for the paper world, merely substituting for human hands and minds. Before they could really pay off, administration and production had to be redesigned both physically and in their command structures. Slowly, the whole process of producing, designing, delivering, and marketing goods and services was, and still is being, reorganized along lines dominated by computing technologies. As more and more of the needed changes in the facilitating structure are identified and accomplished, we can expect that, as with electricity, the latent power of the new technology to raise productivity will be seen in measured productivity growth—as it is in many sectors already.

A. The Organization of Firms

Administratively, the old hierarchical firm, organized on the military command model in which large numbers of middle managers passed information and commands up and down, has given way to the new, more flexible management form of semi-independent groups linked laterally rather than vertically. Many middle managers have lost their jobs in the process.

---

[22] Plus the very early stages of the biotechnology revolution.

Another example is provided by Deiter Ernst (2001) in has paper for this conference:

> **"During the critical early phase, FDI exposed Taiwanese workers and managers to new organizational techniques, gradually eroding traditional, highly authoritarian and ultimately inefficient management practices. Over time, the need to comply to some minimum international quality standards gave rise to broader learning effects that spilled over to a wide spectrum of local enterprises due to the high turnover in Taiwan´s skilled labor market."**

This is typical of the kind of shock that technological change administers to organizational techniques. It shows the endogenous nature of technological change and the importance of openness in forcing producers to learn about and adopt the standards of world markets—a problem that is non-existent in those neoclassical growth models that assume that the same production function applies to all countries in the world.

Ernst (2001) provides another excellent example that illustrates the power of GPTs.

> **"Historically, small, family-owned firms have played an important role in the development of Taiwan´s electronics industry. Yet, this from of business organization is now coming under increasing pressure, and appears to be ill-equipped to deal with the new competitive requirements. Family bonds erode, especially when the firm has to move production overseas and loose networks between family-owned SMEs are unable to raise the capital required for increasing fixed investments and R&D outlays. As a result, Taiwanese SMEs had to develop a variety of linkages with third parties and to experiment with new forms of managing inter-organizational linkages. In what follows, we will highlight three peculiar developments: *informal peer group networks*; integration into loose *cross-sectoral* conglomerates; and the development of *sector-specific* business groups."**

This is similar to what happened in late medieval and early modern Italy where the emergence of new kinds of long distance commerce put stresses on the traditional family methods of doing business. Eventually these gave way to methods that allowed strangers to participate in business ventures in ways that were seldom needed before. As is typical in such changing situations, those who were able to innovate in new institutional structures more suited to the new demands of technology and commerce prospered and those who could not languished.

That much has already happened. The uncertainties attached to the structural impact of major innovations are clearly seen in conjectures about what kinds of organizational adjustments will occur in the future as a result of the continuing ICT revolution. For one example, Malone and Laubacher (1998) foresee a fundamental transformation caused by the growth of the "e-lance economy"—an economy dominated by the electronically linked freelancers.

> **The coordinating technologies of the industrial era—the train, and the telegraph, the automobile and the telephone, the mainframe computer—made internal transactions not only possible but also advantageous. …But with the introduction of powerful personal computers and broad electronic networks—the coordinating technologies of the twenty-first century—the economic equation changes (p147). Because information can be shared instantaneously and inexpensively among many people in many locations, the value of centralised decision making and expensive bureaucracies decreases. …the new coordination techniques allow us to return to the preindustrial organisational model of tiny autonomous businesses…conducting transactions with one another in a market…[with] one crucial difference: electronic networks enable these microbusinesses to tap into the global reservoirs of information, expertise, and financing that used to be available only to large companies. (p148) …The fundamental unit of such an economy is not the corporation but the individual. These electronically connected freelancers—e-lancers—join together into fluid and temporary networks to produce and sell goods and services. When the job is done…the network dissolves, and its members become independent agents again, circulating through the economy, seeking the next assignment. (p146)"**

Should anything like this come to pass the structural adjustment would be enormous. There would be:

> **"…fundamental changes in virtually every business function…. Supply chains would become ad hoc structures, assembled to fit the needs of a particular project and disassembled when the project ended. Manufacturing capacity would be bought and sold in an open market, and independent, specialised manufacturing concerns would undertake small batch order of a variety of brokers, design shops, and even consumers. Marketing would be performed in some cases by brokers, in other cases by small companies that would own brands and certify the quality of the merchandise sold under them. In still other cases, the ability of consumers to share product information on the Internet would render marketing obsolete; consumers would simply "swarm" around the best offerings. Financing would come less from retained earnings and big equity markets and more from venture capitalists and interested individuals." (p 150)**

Many e-lance enterprises have already come and gone. The vision of a major e-lance sector, even if it only covers say 20 percent of the whole economy, is unlike anything ever seen since the First Industrial Revolution destroyed the Putting-Out System.

This discussion illustrates that the major structural changes in the organization of productive units is not yet over; that it will continue at a rapid rate; and that there are major surprises yet to come. For example, David Mowery's paper at this conference describes radical changes in the electronics industry, many of which are similar to those just outlined with respect to the e-lance economy.

B. Economies of Scope and Scale

As GPTs have done in the past, the ICT revolution is altering scale economies in complex ways. Whereas economies of scale in manufacturing were a driving force in the post-war expansion of many industries, increasingly they are becoming either non-important or redefined. The introduction of computers and other information technologies, plus the use of advanced materials, have drastically lowered the minimum efficient scale of production for many individual product lines. One firm's fixed costs of computers and other facilities are covered by producing many product lines so that economies of scope become more important than economies of scale.

The organization of service production has also changed dramatically. On the one hand, firms operating on a global scale in law, accounting, and other traditional services are replacing many of the older individual operators. On the other hand, computers, plus a host of related electronic devices such as faxes, photocopiers, and modems allow many independent providers of services to work out of home rather than where their services are consumed. The internet allows these individuals access to masses of information and the ability to interact with others that was formerly only available to employees of very large corporations. If the first industrial revolution took work out of the home, the computer revolution is, at least partially, putting it back, with profound social and economic consequences.

C. Deindustrialization and Servicization

The new technologies have accentuated a trend towards servicization that has been observable throughout most of this century. It has a number of sources. First, the shift is partly definitional. A range of service activities that used to be conducted in-house by manufacturing firms, and so recorded as manufacturing activities, is now contracted out to firms specialized in activities such as product design, marketing, accounting, cleaning, and maintenance, and so recorded as service activities. Second, on the demand side, the shift to services is partly driven by consumers' tastes. As real incomes rise, people spend a lower proportion of their incomes on durable consumers' goods and a rising proportion on such services as medical care, travel, and restaurant eating. Third, on the supply side, the decline in employment in manufacturing is partly a measure of its success in producing more with less inputs, especially labor. Fourth, also on the supply side, the ICT revolution has encouraged many service activities by making them more efficient.

D. Locational Effects: Globalization[23]

Globalization, the rapid acceleration of a process that has also been going on for over a century, is due in large part to the ICT revolution. The effects on manufacturing follow from four distinct developments. First, the new ICTs have allowed production to be disintegrated into a series of independent operations. Second, ICTs allow independent units to be co-coordinated in ways that were impossible in the past. Seventy five years ago, even where production was split between many component suppliers, these had to be located within relatively short distances of each other so that components could be delivered to assemblers when and where they were required. Third, improvements in transportation technologies, particularly containerization and the development of very large ships, have greatly reduced the costs of shipping goods around the world. Today, with the ability to co-ordinate worldwide and to ship products at very low cost, component parts can be produced anywhere in the world in the right quantities and shipped to arrive when and where they are needed with little error. Fourth, economic policy has changed in most countries in the direction of openness. Trade barriers have been drastically reduced and foreign investment made easier and less threatened by nationalistic policies of harassment or confiscation. Those LDCs that have opened most and earliest, such as the Asian NICs, have prospered most. Those that have stayed relatively closed have prospered least. It is a sad travesty that the energies of so many youth are currently directed at harassing the very developments that have brought relative prosperity (judged by historical standards) to so many in less developed countries. Energies would be better directed to pressuring their own governments to lower the remaining trade barriers that prevent the poorest countries from exporting the products in which they have comparative advantages, particularly agricultural commodities and textiles.

Many services are also globalizing. Ireland, the Caribbean, and India are all locations in which large transnational corporations, such as credit card and travel companies, do much of their record keeping and accounting. Software firms are also moving much of their coding work to places outside of North America. While India is still a relatively small producer of software in absolute terms, it is now one of the fastest growing sources of computer code in the world. When an Indian technician uses the Internet to repair some electronic equipment in Boston, where does the production take place? Where is the value created? Where should it be taxed?

Dieter Ernst (2001) provides an excellent example of globalization.

> **Globalization in the computer industry has culminated in an important organizational innovation, the spread of *global production networks* (GPN) that integrate geographically dispersed, yet concentrated and locally specialized clusters. Their main purpose is to**

[23] I have discussed the implications of the new ICTs on globalization at length in Lipsey (1997)

> **exploit *complementarities* that result from the *systemic* nature of knowledge (Antonelli, 1999). Under certain conditions, these networks may enhance the *migration* of *knowledge across firm boundaries* and *national borders*; they may also improve the opportunities for knowledge sharing and interactive learning *without* co-location.**
>
> **A global *network flagship company* breaks down the value chain into a variety of discrete functions and locates them wherever they can be carried out most effectively, where they improve the firm's access to resources and capabilities, and where they are needed to facilitate the penetration of important growth markets. The main purpose is to gain *quick access* to *lower-cost foreign capabilities* that are *complementary* to the firm´s own competencies. Consider a stylized GPN: it combines a large, multi-divisional MNE (the *flagship*), its subsidiaries, affiliates and joint ventures, its suppliers and subcontractors, its distribution channels and value-added resellers, as well as its R&D alliances and a variety of cooperative agreements, such as standards consortia.**

None of this would have been possible without the communications networks provided by the ICT revolution. Can anyone doubt that these are big changes affecting many aspects of economic and social life?

E. Labor

Flexible, knowledge-intensive production techniques and a global market in the products produced by low skilled labor have led to a need to redefine the role of the union. No longer are strict, rigid job descriptions a supportable labor practice. Skill requirements for previously low-skilled jobs have risen as design, production and marketing increasingly involve creating and processing information.

Effecting the required changes quickly has been a conflict-ridden process. To many labor leaders, the need to change procedures that were worked out painfully early in this century, and that worked well for subsequent decades, seems like some plot to exploit employees instead of an inevitable adjustment to new technologies.

Both firms and workers are going through an evolution where structural relationships are adapting to changes in the technology. Currently it is the well paid and well educated who are benefiting most from the introduction of the computer in the work place and thus, computerization is reinforcing the polarization of incomes and jobs. Dealing with long-term unemployment and finding ways to diminish the proportion of the labor force which is unskilled and, therefore, in competition with unskilled labor world-wide are urgent matters for public policy in the developed nations.

F. Social Organizations

Ways of life are changing with the changing patterns of work. With electronic communication, groups of like-minded individuals are finding it easier to get together.

Technologies have effectively redefined our notions of time and distance (and in some ways have created the much-heralded global village).

> **By linking people and groups, e-mail encourages work across space, time and group boundaries. Indeed, the absence of constraining non-verbal cues and social controls in e-mail may make it easier to communicate with unknown or peripheral people than through face-to-face means. Such wide-ranging ties are especially useful for linking socially diverse people, obtaining innovative information and integrating organisations. (Wellman & Buxton, p.12)**

G. Policy

Here are three illustrations of the profound changes in existing public policies that are occurring in response to current technological changes. First, the sophisticated communications produced by the ICT revolution, and the globalization that it has facilitated, make it impossible for governments to control international capital movements in the ways that they routinely did in the era of fixed exchange rates. Second, the increasing difficulty that governments face in dictating what their citizens will see and hear has curtailed the efficacy of information-restriction policies exercised by both dictatorships and democratic governments. Third, the assets that confer many of today's national competitive advantages tend to be both created and highly mobile. This severely restricts any individual government's ability to adopt policies that affect the value of these assets and that differ markedly from policies followed by other governments.

H. Productivity

Great concern has been expressed over the slow measured increase in productivity in most industrialized economies over the last 21/2 decades of the 20th century. Indeed, many observers, e.g., Robert Gordon (2000), have used these low figures to argue that the alleged fundamental transformations caused by the ICT revolution are so much hype. Such views are clearly in strong opposition to those I have expressed in this paper (and at many earlier times. I make three points about the "productivity paradox". The fist two summarize what has been said before; the third is new.

First, very long lags exist (i) in the development of a major GPT as the range of its use and applications evolves (ii) as ancillary technologies are developed and (iii) as changes are made in all of the elements of the facilitating structure. Typically, several decades are required for a GPT to make a major impact—and that impact may then stretch over more than a century as new technologies that are enabled by the GPT are developed. (Electricity is a prime example.)

Second, and more fundamentally, a new technology will be instituted whenever it promises to be profitable. But there is no guarantee that every new technology will have the same effects on profits and productivity (however it is measured). Some technologies will bring small gains, others large gains. So the extent to which the new technology pervades the system and the extent of the induced changes in the facilitating structure, right up to deep social transformations, bear no necessary relation to the induced changes in productivity or real wages. (For example, as pointed out earlier the major technological changes of the early Industrial Revolution were associated with small changes in productivity while the small technological changes associated with the introduction of steam engines into factories were associated with large changes in productivity.) There is only a paradox when neoclassical theory, which equates technology change with changes in TFP, is used to interpret what is going on.

Third, total factor productivity is a very poor measure of the effects of technological change. (This is argued in detail in Lipsey and Carlaw 2000.) we begin that paper by showing that economists are not agreed on what TFP measures. Krugman (1996), Alwyn Young (1992), Statistics Canada (13-568) and Law (2000) all express the common view that TFP measures all technological change. Jorgenson (1995) and Griliches (1994) argue that TFP only measures the externalities associated with growth. Metcalfe (1987) argues that it is only valid over short periods of time. While, in another publication, Griliches (1995) states that it is little more than a measure for our ignorance.

It is something of an understatement to say that all of these views cannot be correct. TFP means different things to different informed observers but all too many have no hesitation in agreeing that low TFP numbers show a low rate of technological change. Surely it is a scandal that a measurement that is so much relied upon is so poorly understood.

After an extended analysis that shows many ways in which technology can change without being reflected in TFP changes, Lipsey and Carlaw (2000) conclude, among other things:

- **All improvements in technology, such as the internal combustion engine, do not "clearly raise TFP.**

- **There is reason to suspect that TFP does not adequately reflect the increase in a firm's capital value created by R&D activities that are realised through sale of intellectual property rather than exploitation by the firms that develop them. Yet these are often technological advances created by the use of valuable resources.**

- **TFP does not adequately capture the effects on the growth process of those technological changes that operate by lowering the cost of small industries and then allowing large subsequent increases in their sales and outputs, as happened in the automobile industry between 1905 and 1925.**

- **TFP does not adequately measure the massive amount of technological change that gets embodied in physical capital where the change is, under some circumstances, recorded as an increases in the quantity of capital rather than an increase in productivity.**

- **When full, long-run equilibrium does not pertain, as in the midst of any lagged adjustment process, the marginal equivalencies needed for successful aggregation do not obtain and it is likely that some of the increases in productivities of labour and capital will be recorded as increases in the quantities of labour and capital.**

- **New technologies often lead to large up front costs of R&D and learning by doing and using that are incurred in the expectation of future benefits that will be missed when current outputs are related to current costs. The amount of this activity may vary with the life cycle of GPTs and this will affect measured TFP.**

- **Neither TFP nor externalities adequately measure the technological complementarities by which an innovation in one sector confers benefit on other sectors—benefit for which those in other sectors would be willing to pay but do not have to do so.**

> **It seems to us that, whatever TFP does measure—and there is cause for concern as to how to answer that question—it emphatically does not measure all of technological change. While people are, of course, free to measure anything that seems interesting to them, the degree of confusion surrounding TFP, particularly the assumption that low TFP numbers imply a low degree of technological dynamism, would seem to us to justify dropping the measure completely from all discussions of long term economic growth. Even if that does not happen, as we are sure it will not, every TFP measure should carry the caveat: *changes in TFP do not measure technological change.”***

I. Conclusion

The scale of R&D in the new applications of ICT, the extraordinary growth of the software industry and related business services, the scale of investment in computerized equipment and in the telecommunications infrastructure, the rapid growth of industries supplying the ICT products and services and the use of computers within every function in every industry have led some observers to characterize the ICT Revolution as a structural change in the economy comparable to the First Industrial Revolution. Peter Drucker argues, with not much exaggeration, that:

> **“We are clearly in the middle of this transformation...already it has changed the political, economic, social, and moral landscape of the world. No one born in 1990 could possibly imagine the world in which**

> **one's grandparents...had grown up, or the world in which one's own parents had been born." (Drucker, p 3)**

The future is hard to predict but the ICT revolution is still in full swing. Many applications to new products new processes and new ways of organizing activities are yet to be invented. Their effects will continue to reverberate through most economies during the first half of the 21st century. As the century proceeds, these effects will be combined with those coming from two other major GPTs, first biotechnology, then nanotechnology.

V. POLICY IMPLICATIONS OF ENDOGENOUS TECHNOLOGICAL CHANGE

Neoclassical GE theory of the type developed by Arrow and Debreu underlies neoclassical policy advice. In that theory, tastes and technology are exogenous and competitive forces lead to an optimum allocation of resources. The theory abstracts from all of those characteristics that distinguish one economy from another, such as stage of development, size of economy, industrial concentration, prevalence of entrepreneurial talent, and administrative capabilities to run government policies. The resulting universal policy prescription is to alleviate market failures that prevent the optimum allocation from being achieved.[24]

Two branches of dissent can be distinguished. On the one hand, Romer's branch of new macro growth theory stresses the nature of knowledge as being non-rivalrous and partly appropriable. He points out that in many models the associated problems are ignored by treating knowledge like any other fully rivalrous private good that confers externalities. On the other hand, the structuralist-evolutionary theory considered in some detail above, is micro based and stresses the uncertainty that is associated with technological advance. Both Romer's and the S-E approaches conclude that the neoclassical optimal allocation of resources is unachievable in theory, let alone in practice, and hence the policy advice of removing impediments to achieving that optimum is not well grounded.[25]

A. General Implications

If endogenous technological change lies at the heart of economic growth, as stressed by S-E theory, governments cannot avoid influencing growth since almost every government policy, including those related to education, competition, and redistribution, will have some influence on the amount, location and direction of technological change. Writing in

---

[24] The theory of second best (Lipsey and Lancaster 1956) is a skeleton in the closet of this type of piecemeal policy advice. Since a first best optimum is in practice unachievable, there is no guarantee that removing any one source of "market failure" will move the economy towards rather than away from the optimum.

[25] I have compared and contrasted these theories in some detail in Lipsey 2000.

1834, John Rae, one of the first economists to perceive the implications of endogenous technological change, said:

> **"Instead of pursuing a policy of non-intervention, the 'legislator' should stimulate foreign trade and technical progress, encourage the transfer of knowledge, tax luxuries, and use tariffs to protect infant industries." (John Rae 1834.)**

Schumpeter and other theorists of endogenous technical change have typically followed the direction (if not the specifics) of the policy route pointed to by Rae. Thus, the substantive policy issue today is not "Is technological change endogenous?" but "Given that it is, what is the best government policy response?".

B. Advice for Developing Countries

1. Focussed policies

The theories in the S-E tradition suggest a need for more focused policies (it being always understood that these are in addition to, not substitutes for, the type of market-orienting measures included in what John Williamson long ago called the Washington Consensus). In contrast to the universalism of neoclassical policy advice, S-E theories suggest the following:

- Accepting the conclusion that there is no unique optimum allocation of resources (because of the non-rivalrous nature of knowledge as emphasized by Romer and because of pervasive uncertainty surrounding technological change as emphasized in S-E theory) implies that there are no unique optimum rates of R&D, of innovation, and of diffusion. Policy with respect to these matters must, therefore, be based on a mixture of theory, measurement and subjective judgment.
- Accepting that new technological knowledge, whether acquired from abroad or produced by domestic R&D, has major positive externalities provides a reason to encourage technological advance with public funds.
- Accepting that technology changes endogenously provides a reason why present comparative advantage need not be accepted as immutable; it can be changed by public policy as well as by the activities of private agents.
- Accepting that technological change is highly dependent on local contexts implies that the best policies are context specific rather than being the same for all countries at all times.

These ideas are both powerful and dangerous. They are powerful because they suggest ways to go beyond neoclassical generic policy advice to more context-specific advice. They are dangerous because they can easily be used to justify ignoring advice forgetting that the interventionist part of the S-E policy is meant to supplement the advice of the Washington Consensus, not to replace.

2. Catch up versus leading edge advance

Developing economies are mainly concerned with technological catch up, which is a diffusion problem. In contrast, economies at the cutting edge of new technologies must deal with issues related to novel discoveries and path breaking innovations. Although, as pointed out earlier, there is no sharp line between invention of new technologies and diffusion of existing ones, there are still differences between the problems facing an economy mainly concerned with technological catch-up and one concerned with cutting edge developments. For example, although there are some uncertainties associated with the local adaptations of technologies already in use elsewhere, many of the main uncertainties that were associated with making these cutting edge advances have already been resolved. What matters is that many appropriate policy requirements—from the most appropriate type of intellectual property rights, assistance to firms, education for the labour force, university departments and government research laboratories—differ between economies in catch up and cutting edge situations.

Here is one example. Many catch-up Asian countries have used consultative processes whereby a government agency (MITI in Japan's case) and the main private sector agents came to a consensus on where the next technology push should be. The parties then jointly financed the required research. This policy worked well in the many catch-up situations for major technological advances, and it still works well when all private agents are pushing for a *fairly well defined* small-to-intermediate advance in pre-competitive technological knowledge. Consensus and co-operation can then reduce wasteful duplication of research. (For further discussion see Lipsey and Carlaw 1996 and Lipsey and Wills 1996.) But when major breakthroughs at the cutting edge are being sought, the uncertainties are better coped with by a multiplicity of investigations, each pursued with the minimum required resources. In such cases, concentrating effort, even after a national consensus has been reached, has often produced poorer results than those produced by the apparent "wastefulness" of uncoordinated experimentation that occurs in the free market.

Many confusions can arise from the failure to accept that appropriate policies vary as between catch-up and leading-edge situations. Here are two illustrations. First, there is a danger of drawing the wrong lesson when a country's institutions that worked well at the catch-up stage begin to run into trouble at the cutting edge (as are many of Japan's). Neoclassical economists often conclude that the policies are finally being shown to be bad policies in general, rather than that the policies are no longer appropriate to the new circumstances. Second, no country has all of its industries at the leading edge, although some countries may have all of their industries at the catch-up stage. More typically, countries have a mix of some leading edge, some catch-up, and some stagnant industries. This creates a serious danger of misinterpreting the evidence when policies appropriate to one sector fail in another. The policies may have been wrong for the sector in which they were applied but not wrong in other contexts.

3. The infant industry argument reconsidered

Another example of how S-E theory puts new light on appropriate development policies concerns the infant industry argument for protecting the home market for newly developing industries.[26] Economists have usually sought to rationalize this argument by appealing to static economies of scale (thereby begging the question of why private finance could not be raised to allow firms to attain a size sufficient to exploit the scale economies implicit in existing technologies). The real significance of the infant industry argument turns on two aspects emphasized in S-E theory. The first is endogenous technological change. When technological change is endogenous, the encouragement of a successful infant industry, such as electronics in Taiwan, can *shift* the local cost curve downwards as new technologies are developed that produce at lower cost than anything previously in existence. This is not an easy thing to do, as is attested by countless failures to develop such industries through public policy. But neither is it impossible, as is attested by some major successes such as the post-second-world-war Japanese car industry and Taiwanese electronics. The main point is that standard text book treatments miss-state the infant industry problem as one of moving along a pre-existing, negatively sloped, long-run cost curve (based on constant technology). Whereas the real problem is to develop an industry whose rate of technological change (shifting cost curves downwards as well as developing new products) compares favorably with those of its foreign competitors.

The second aspect of S-E theory that is relevant to infant industries concerns the dynamic path that an industry must follow as it develops through the creation and acquisition of both technologies and the related elements of the facilitating structure, including human capital. New technologies develop out of, and are placed into, the facilitating structure. Many of the benefits from creating new elements of that structure cannot be reaped by those who do the creating. There are many externalities some of which take the form of scale effects. For example, an isolated firm may find invention and innovation difficult. A growing cluster of related firms may find it much easier for several reasons. Technicians can trade inside knowledge (vonHipple 1988), a trained labour force will be evolving, and the supply of entrepreneurs will sooner or later reach some critical mass. Thus, creating many elements of the facilitating structure imposes net costs on the firms that begin a cluster and gives net benefits to firms that enter the cluster later. Infant industry protection, provided it is judiciously applied and sunsetted, can assist in developing a structure that would not arise solely from profit-motivated actions by private firms who create more value in the structure than they themselves can benefit from .

---

[26] As a matter of fact, few countries have developed a modern industrial structure without a protective tariff at the early stages of their development. Many countries, including the US, went through the early stages of industrialization with substantial tariff protection for its infant industries. Indeed, even in the UK, the subsequent home of free trade, the prohibition on the importation of Indian cotton goods was an important incentive for the development of the machines that produced the First Industrial Revolution.

C. Political Structure Matters

Another important way in which appropriate policy is context specific in both developed and developing economies concerns political structure. What a government is capable of depends on a number of things. One important influence is the basic constitution. For example, the US government was successfully designed by its framers to severely limit the power of the administration, while Parliamentary systems give much power to the party in power but have their own characteristic limitations. What governments are able to do effectively also depends on the competencies and experiences of their civil servants. It also depends on how easy it is for special interest groups to capture specific policies and turn them to their own uses.

Thus, the public sector institutions in different countries have different institutional capabilities, partly based on constitutional differences—e.g., US or English style governments—partly on the county's geography—because central governments of large and diverse federations with strong regional governments must broker regional interests in ways that are not required in smaller more homogenous countries—partly on power relations between various special interest groups, partly on the nature of their civil service recruitment policies, and partly on the administration's accumulated learning by doing in operating their country's typical set of policy instruments.

This discussion of institutional capabilities shows that it is not enough to have policies that are well designed in the abstract. Policies must work through an institutional structure and their success depends to a great extent on the institutional competencies of those administering them. The discussion also suggests that, as long as they are understood to be talking about the institutional capabilities of their own public sectors, US economists may be right in asserting that minimal government is preferable to even moderately activist government, while Asian economists may also be right in asserting the opposite. This is yet another example of the context-specificity of good policies and of how misleading is the neoclassical assumption that there is one set of policies that is optimal for all countries at all times.

END OF TEXT

BIBLIOGRAPHY

Antonelli, C. (1998), *The Microdynamics for Technological Change*, (Routledge: London).

Arthur, B. (1988), "Competing Technologies: An Overview," in *Technological Change and Economic Theory*, G. Dosi et al (eds), (London: Pinter).

Blaug, Mark (1997), "Competition as an end-state and competition as a process," in *Trade, Technology and Economics: essays in honour of Richard G. Lipsey*, B.C. Eaton and R. Harris (eds.) (Cheltenham: Edward Elgar).

Drucker, Peter F. (1993), *Post Capitalist Society*, (New York: HarperCollins)

______________ (1998), "The next Information Revolution," *Forbes* ASAP, 24 August, 47-58

Eatwell, J., M. Milgate, and P. Newman (eds.) (1987), *The New Palgrave, a Dictionary of Economics*, (London: Macmillan).

Ernst, Dieter (2001), "Inter-Organizational Knowledge Outsourcing" background paper for the workshop on the internet

Freeman, C., and C. Peres (1988), "Structural Crisis of Adjustment" in *Technological Change and Economic Theory*, G. Dosi et al (eds), (London: Pinter).

Gordon, R.E., (2000), "Does the "New Economy" Measure Up to the Great Inventions of the Past?" *NBER Working Papers*, no. 7833.

Griliches, Z. (1992), "The Search for R&D Spillovers," *Scandinavian Journal of Economics*, 94 (supplement), 29-47.

__________ (1994), "Productivity, R&D, and the Data Constraint", *American Economic Review, 84 (1)*

__________ (1995), "The Discovery of the Residual", *NBER Working Papers*, no. 5348

Jorgenson (1995) *Productivity, Volume 1: Postwar U.S. Economic Growth* (Cambridge: MIT Press)

Helpman, E. (ed) (1998), *General Purpose Technologies and Economic Growth*, (Cambridge: MIT Press)

Krugman, Paul, (1996) "The Myth of Asia's Miracle" in *Pop Internationalism* (Cambridge: MIT Press)

Law, M. T. (2000), Productivity and Economic Performance: An Overview of the Issues, *Public Policy Sources*, No. 37.

Lipsey, Richard G. (1996), *Economic Growth, Technological Change, and Canadian Economic Policy*, (Toronto: C.D. Howe Institute).

_______________ (1997), "Globalization and National Government Policies: An Economists View," in *Governments, Globalization, and International Business*, John Dunning (ed.), (Oxford: Oxford University Press).

_______________(1999) "Sources of Continued Long-Run Economic Dynamism in the 21st Century" in *The Future of the Global Economy: Towards a Long Boom*, Wolfgang Michalski, (ed.) (Paris: OECD).

_______________ (2000), "New Growth Theories and Economic Policy for the Knowledge Economy", in *Transition to the Knowledge Society: Policies and Strategies for Individual Participation and Learning*, Kjell Rubenson and Hans G. Schuetze (eds), (Vancouver BC: University of British Columbia Press).

_______________ (2001), "Economies of Scale in Theory and Practice," available at http://www.sfu.ca/~rlipsey

_______________ and Clifford Bekar (1995), "A Structuralist View of Technical Change and Economic Growth" in *Bell Canada Papers on Economic and Public Policy,* Vol. 3, (Kingston: John Deutsch Institute), 9-75.

_______________ and Kenneth Carlaw (1996), "A Structuralist View of Innovation Policy," in *The Implications of Knowledge Based Growth*, Peter Howitt (ed.), (Calgary: University of Calgary Press), 255-333.

_______________________________ (2000), "What Does Total Factor Productivity Measure?" available at http://www.sfu.ca/~rlipsey

_______________ and K. Lancaster (1956), "The General Theory of Second Best", *The Review of Economic Studies*, 1956, **24**, 11-32.

_______________ and Russel M. Wills (1996) "Science and Technology Policies in Asia Pacific Countries: Challenges and Opportunities for Canada," in *The Asia-Pacific Region in the Global Economy: A Canadian Perspective*, Richard Harris (ed.), (Calgary: University of Calgary Press).

_______________, Clifford Bekar and Kenneth Carlaw (1998a) "What Requires Explanation," Chapter 2 in *General Purpose Technologies and Economic Growth*, Elhanan Helpman (ed), (Cambridge: MIT Press), 15-54.

____ (1998b) "The Consequences of Changes in GPTs," Chapter 8 in *General Purpose Technologies and Economic Growth*, Elhanan Helpman (ed), (Cambridge: MIT Press), 194-218.

____ (in preparation), *Time Technology and Markets: Explorations in Economic Growth and Restructure*

Malone, Thomas W. and Robert J. Laubacher (1998), "The Dawn of the E-Lance Economy," *Harvard Business Review*, September-October, 145-152

Metcalfe, S. (1987), "Technical Change" in, Eatwell, et al (1987), 617-620.

Nelson, R. and S. Winter (1982), *An Evolutionary Theory of Economic Change*, (Cambridge MA: Belknap Press).

Rae, John (1905), *The Sociological Theory of Capital*, (New York: Macmillan). First published in 1834 as *Statement of Some New Principles on the Subject of Political Economy Exposing the Fallacies of the System of Free Trade and of Some Other Doctrines Maintained in the Wealth of Nations.*

Rosenberg, Nathan (1976), *Perspectives on Technology*, (Cambridge: Cambridge University Press).

________________ (1982), *Inside the Black Box: Technology and Economics*, (Cambridge: Cambridge University Press).

Statscan 13-568: 50-51

Schick, K. D. and N. Toth (1993), *Making Silent Stones Speak: Human Evolution and the Dawn of Technology*, (New York: Simon and Schuster)

von Hipple, E. (1988), *The Source of Innovation*, (Oxford: Oxford University Press).

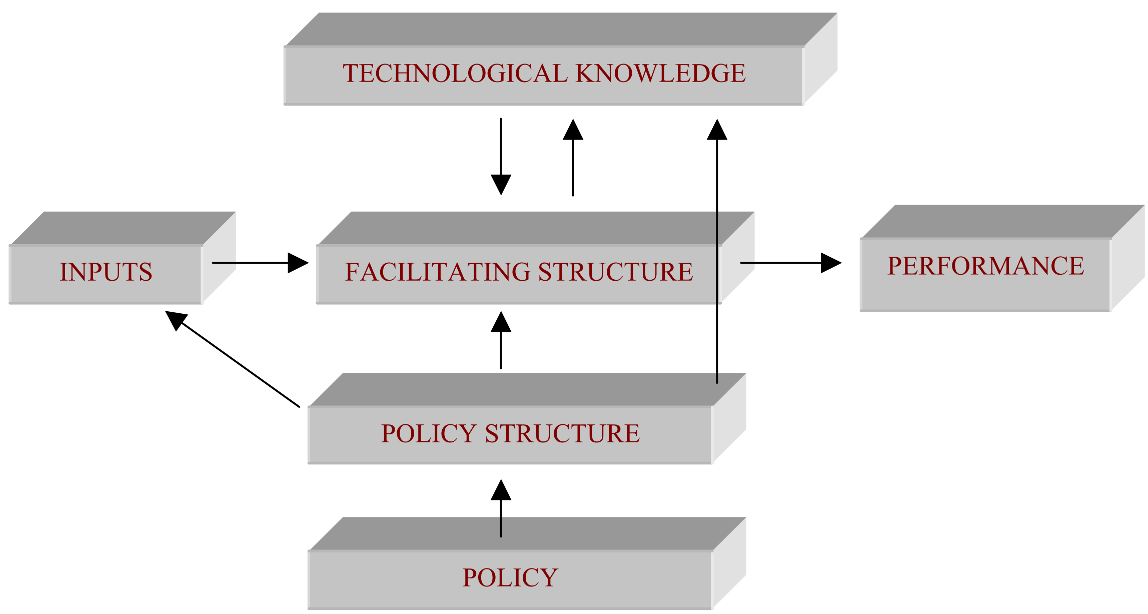
Wellman, B. and B. Buxton (1994), "Work and Community Along the Information Highway," *Policy Options*, 7, 11-15.

Young, Alwyn (1992) "*A Tale of Two Cities: Factor Accumulation and Technical Change in Hong Kong and Singapore*" NBER Macroeconomic Annual (Cambridge: MIT press)

FIGURE 1

Part A

Part B



Caption For Figure 1: Part A shows the neoclassical approach. Inputs of labour, materials and the services of physical and human capital flow through the economy's aggregate production function to produce economic performance, as measured by total national income. The form of the production function depends on the economy's structure and its technology, but these things are hidden in a black box, the only manifestation of which is how much output emerges from a given amount of inputs.

Part B shows our structuralist-evolutionary approach. Technological knowledge is the idea set for all products, process, and organizations that create economic value. The facilitating structure is the realization set and includes the capital goods that embody much of the technology, the internal organization of firms, the geographical location and concentration of industry, the infrastructure, and the financial system. Inputs pass through the structure to produce economic performance. Policy is the idea set of public objectives and the specification of means. The policy structure is the realization set that gives effect to policy, including all kinds of public institutions. Policy, working through the policy structure, influences the facilitating structure, technological knowledge and the quantity/quality of inputs.