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**THE ECONOMICS OF INFORMATION  
TECHNOLOGY: EXPLAINING  
THE PRODUCTIVITY PARADOX**

**Geoffrey M. Brooke**

**April 1992**

**CISR WP No. 238  
Sloan WP No. 3430**

**Center for Information Systems Research**

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# THE ECONOMICS OF INFORMATION TECHNOLOGY

## *Explaining the Productivity Paradox*

### ABSTRACT

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The past forty years have seen dramatic advances in the technology of information processing, and its widespread adoption bears testimony to the advent of the 'information society'. However, the economic implications of this transition remain to some degree obscure, since there is little evidence that the new technology has led to clear improvements in productive efficiency. Indeed, during the past twenty years the United States' economy has suffered from a declining rate of productivity growth, despite sharply accelerating investment in computer-based systems.

Several attempts have been made to resolve this 'productivity paradox', yet none has proved entirely satisfactory. In this work, we propose a new explanation of the paradox, and present economic evidence in its support. The central argument is that information technology has altered the economies of production in favor of differentiated output, and that our methods of productivity measurement tend to discount the benefits of greater product variety. The validity of this reasoning is demonstrated by an empirical study of the United States' private economy, covering the forty-year period from 1950 to 1989. Despite these results, however, we conclude that declining productivity growth is not merely an accounting fiction, since our current economic system is relatively ill-suited to differentiated production.

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## I. INTRODUCTION

Is America losing its position of global pre-eminence and entering a period of inexorable economic decline? During the past two decades, much attention has been drawn to the signs of America's relative economic weakness – a falling share of world output, growing trade and fiscal imbalances, stagnating real incomes, and a persistently low rate of productivity growth. The growing intensity of international competition is exposing inefficiencies in many American corporations, and is taking a relentless toll of their workers, factories and markets. Distressed by declining living standards and by the uncertainty of their economic future, many Americans look back to the post-war years as a time of unrivalled prosperity that neither they nor their children shall ever see again.

With the steady downward drift of the last twenty years, the general outlook seems unremittingly bleak. Yet it is belied, in some ways, by the promise of a strange new world which is slowly emerging from the shadow of the old.

Reflecting on America's economic record, several observers have been puzzled by the fact that the recent period of lagging productivity growth has also been a time of rapid innovation and technical advance. Far from sheltering from the winds of change, American industry has eagerly invested in new technologies, and especially in those associated with the processing of information. Furthermore, this paradoxical pattern – of technological innovation and economic retardation – has been observed in many nations that have followed the American example, and has led some critics to question the ability of the new technology to generate an economic return.

Is this new world – a world of information – one which confounds our traditional presumption that technological progress and productivity growth go hand in hand? If so, are we condemned to accept an ever-growing burden of information, which encumbers our efforts to improve economic performance and to respond to agile new competitors in the global market-place? Or might we not be better advised to throw off the yoke of information technology, and return to the tried and trusted ways that were the foundation of past successes?

It is our purpose here to address these questions, with the aim of explaining the origins and nature of our current economic predicament. In particular, we shall explain the underlying cause of America's declining rate of productivity growth, and shall also suggest (1) why this decline became noticeable after 1973, (2) why it persists to the present day, and (3) why this experience has been shared by many of the world's developed economies. More generally, our analysis may provide the basis for a deeper understanding of the productive role of information, and thus of the economic system that will define the shape and substance of the new America.

## II. EXPLAINING THE PRODUCTIVITY PARADOX

The quarter-century following the Second World War ranks as a remarkable period in economic history. Buoyed by rising capital investment, increasingly open international markets, stable exchange rates and a variety of other factors, many of the industrial nations enjoyed an unprecedented improvement in the general welfare of their citizens. Although many influences contributed to this improvement, its ultimate basis was a sustained rise in the productivity of the resources employed within the general economic system. Each successive year, these resources were able to generate higher and still higher levels of output: in the American case, relative to the

amount of effort required from the average worker, the national economy produced some 3% more every year – providing benefits such as higher real wages, better social services and, in general, a more equitable distribution of income.

After 1973, for reasons which have since been much debated, this era of steady economic progress came to an end. America's average rate of productivity growth fell from 3% to 1% per annum, and a similar decline was observed in many nations at a comparable stage of economic development. However, while the American growth rate has remained at this relatively low level, in other economies – especially in those of its major international competitors – productivity growth has regained much (though not all) of the lost ground. In consequence, America's position in global trade has steadily weakened, leading to diverse forms of economic hardship and a growing concern that the downward trend – or 'productivity slowdown' – may signal a permanent loss of productive efficiency.

### Leading Explanations of the Slowdown

Prompted by these considerations, several prominent economists<sup>1</sup> have attempted to analyze the causes of America's post-1973 decline. For example, attention has been directed at changes in key economic inputs (e.g., rising energy prices, deteriorating labor quality, reduced capital investment, etc.) that may have undermined the productive capabilities of the national economy. However, although several of these factors have clearly contributed to a general falling-off in the rate of productivity growth, neither alone nor in combination have they been able to explain a major proportion of the total decline.

This inconclusive evidence has lent support to an alternative argument<sup>2</sup>, which proposes that it is neither inferior nor more costly inputs, but a *structural change* in the economic system itself, that is the root cause of America's productivity problem. The essential reasoning is that the high levels of productivity growth experienced between 1948 and 1973 allowed the pattern of economic activity to shift away from capital-intensive, high-productivity sectors (such as manufacturing) toward labor-intensive, low-productivity sectors (such as those providing information and other services). Prior to 1973, the size of the former was such that its productivity gains were sufficient to overcome any shortfall in the performance of the latter: but as the manufacturing sector shrank, and the services sector became economically predominant, a decline in the productivity of the total system was, in the end, inevitable.

The theme of structural change has also been evident in the writings of those<sup>3</sup> who have studied America's growing reliance on information technology. Since there appears to be little direct evidence that the enormous technological investment of the past twenty years has served to arrest the economy's downward slide (the phenomenon that is now known as the *productivity paradox*), it is proposed that the new technology has contributed to – indeed, has been a central cause of – the steady shift toward service-intensive economic activities. In consequence, some have seen cause to doubt the economic value of information technology, claiming that it has allowed the services sector to develop an inefficient, fixed-cost infrastructure that inhibits competition and the productive re-deployment of capital and labor resources.

As an explanation of the 'productivity slowdown', the thesis relating structural change, services and information technology does have a certain plausibility: the American economy of the 1990s is clearly quite different, as

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<sup>1</sup>For example, Denison (1982) and Baily (1986).

<sup>2</sup>This takes a variety of forms – see, e.g., Baumol (1967); Thurow (1981); Tyler (1981); Jonscher (1983); Baumol, Blackman & Wolff (1985).

<sup>3</sup>Baily & Chakrabarti (1988); Baily & Gordon (1988); Loveman (1988); Roach (1988, 1991); Berndt & Morrison (1992).

regards the importance of information and services, from its predecessor of the 1950s. Yet despite the prima facie evidence in its favor, the service-economy argument leaves certain questions unanswered. Why, for example, have more (and, perhaps, better) services been preferred to higher productivity growth? And why, in particular, have services been preferred if lagging productivity leads to stagnating real incomes and to a generally lower standard of living?

To these objections, several responses are possible. One retort might be that the shift to services has in fact raised living standards, not lowered them: it is only the intangible nature of many service outputs that prevents accurate measurement of the associated gain in welfare. On this basis, the 'productivity slowdown' is largely a fiction of crude accounting, and we are much better off than the national economic statistics suggest. A related proposition might be that America, in common with other advanced economies, has seen a maturing of consumer tastes, manifested by a declining market for basic commodities and a rising demand for sophisticated (yet more costly) service products.

We might perhaps be persuaded of this, were we not at the same time confronted by the American consumer's undiminished appetite for tangible, non-service products. As is well known, during the past decade the international trading position of the United States has noticeably deteriorated, owing in the main to the popularity of imported goods: only an insignificant proportion of this growing deficit can be attributed to an increased consumption of services<sup>4</sup>. Furthermore, services are in fact only a small component of final demand: most service outputs are provided as intermediate inputs to the goods-producing sector<sup>5</sup>. In this context, the 'service economy' seems, to some extent, an illusion: and the efficient production of physical goods still appears to be the real foundation of economic success<sup>6</sup>.

For this reason, we would argue that the national productivity shortfall reflects an underlying economic weakness, not merely inaccurate measurement or changing tastes. Indeed, whatever the basis of calculation (provided it is applied consistently across countries), any nation whose rate of productivity growth falls significantly behind the rates achieved by its major economic rivals, will find its ability to compete in global markets progressively compromised. Our primary need, therefore, is to understand why a *real* decline in productivity growth has accompanied the emergence of a society in which goods, services and information appear to be co-ordinate in the economic process. To this end, however, we must first explain the extent to which the decline *is*, in fact, attributable to a rise in the production of unmeasured, service-related outputs.

### The Meaning and Measurement of Productivity

At the most elementary level, our concern with productivity growth stems from our interest in reducing the sacrifice that must be made in the present if we are to enjoy the benefits of consumption in the future. With this in mind, productivity is often defined as the ratio of 'outputs consumed' to 'resources expended': the outputs comprising the various goods and services that are purchased by consumers, and the resources (or inputs) being the materials, energy and human effort that are used in their production. In practice, this productivity ratio takes many particular forms, but for our present purposes we shall concentrate on an important variant known as *labor productivity*, or 'output per hour'. This ratio relates the monetary value of final demand (i.e., consumer purchases, business and government investment, and net exports) to the number of hours spent at work (by those

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<sup>4</sup>Cf. Quinn (1988, p. 39, Table 6).

<sup>5</sup>Jonscher (1983, p.17) estimates that 85% of the output of the 'information' sector is returned to the goods sector. Duchin (1988, p. 79, Table 1) provides similar data for other industries within the services sector.

<sup>6</sup>Baumol, Blackman & Wolff (1989, Chapter 6) argue that the services-sector's growing share of the national product reflects a change in the relative prices of goods and services, not a change in their relative real outputs.

employed in production), and is a fundamental indicator of the wealth-generating capacity of a nation's labor force.

Turning now to the question of measurement, the calculation of labor productivity clearly depends on the accurate estimation of both 'output' and 'hours at work'. Although the latter variable presents a number of difficulties of its own, we shall not dwell on these since our current focus is the changing nature of economic outputs, given the trend toward service-intensive production. Concentrating therefore on the measurement of output, we may observe that the variable is expressed in monetary terms, and thus is subject to the distortions of price inflation. Clearly, to obtain a reliable measure of economic output and its fluctuations over time, it is essential to eliminate such effects since they are often very large relative to any rise in the true productivity level.

In practice, the problem of price inflation is solved by examining, within each economic sector, the year-to-year change in product prices and then discounting, from one year to the next, any increase in price that does not correspond to a change in product specification<sup>7</sup>. For example, if the same model of car is priced at \$10,000 in the first year and \$10,200 in the second, then the extra \$200 is discounted as pure inflation and the price of the car, expressed in 'constant' dollars, remains at \$10,000. However, if in the second year the specification of the car is altered to include a \$200 radio as standard equipment, then no deflation procedure is applied (the radio being regarded as a quality improvement) and real output rises by \$200.

Over the years, this method of quality-adjusted price deflation has been employed with considerable success. It suffers however from an acknowledged deficiency, in that no allowance is made for quality improvements *which are not directly associated with a production cost*. For example, instead of installing a radio as standard equipment, a car manufacturer may offer a *choice* of radios, thus allowing the customer to satisfy a preference for a radio of some particular type. From our present perspective, this deficiency is important because many service-related improvements are of precisely this type: they arise, not from any tangible change in the nature of the product itself, but from the provision of additional services that make the product more convenient, more accessible, or generally more valuable to the individual consumer.

At this stage it is vital to note that the discounting of indirect-service benefits is *not the same* as the mis-measurement of intangible service outputs. To elucidate this point, we may observe that the output of many service industries and professions – law, medicine, finance, entertainment, public administration, education etc. – is largely intangible and hence not susceptible of measurement in any quantitative sense. Clearly, any rise in the consumption of such services will tend to aggravate the measurement difficulty, and render estimates of productivity growth all the more suspect. Yet it is also clear that where a service component is included, indirectly, as part of a non-service product, the effect on output measurement will be equally unfortunate, although there may be little apparent change in the relative consumption of goods and services.

The significance of this last point lies in the following. If we can show that, after 1973 and for certain reasons, there was a substantial rise in the 'indirect-service' element of production, then we may conclude that unmeasured (i.e., improperly deflated) output has increased as a proportion of the national product, without there being any unwarranted shift (from goods to services) in the pattern of final demand. We may then attribute the actual growth of the services sector to a greater use of indirect inputs to the productive process, and explain the role of inadequate measurement in the post-1973 decline in American productivity growth.

Our next task therefore is to examine the nature of this indirect-service element – to which we shall apply the term *product differentiation* – and to explore its connection with *information*, recalling our earlier concern that information technology has apparently done little to restore America's economic performance to its post-war heights.

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<sup>7</sup>See Mark (1986).

## Product Differentiation and Variety

In common usage, *product differentiation* refers to any activity that serves to distinguish a product from others in the same general market. From the producer's viewpoint, differentiation is desirable because it increases the attractions of his own product relative to the offerings of competitors, and so allows for a higher price and a wider profit margin. The discriminating consumer also gains however, in that the differentiated product is more closely suited to the peculiarities of his situation or taste. In this context, then, it seems clear that the differentiation process is one which causes the product to incorporate 'service' as a native characteristic: indeed, the product becomes more *serviceable*, being of greater utility in relation to its final application.

Now it is evident that certain forms of differentiation involve a tangible alteration to the product – a car is clearly distinguished by the inclusion of a radio – and in these cases the fact of differentiation presents no untoward difficulties in relation to output measurement. Again, certain other forms imply an *intangible* product change – a car may be differentiated by its greater reliability, for example – but, as regards the accuracy of price deflation, this problem has always existed (and methods of dealing with it have, if anything, improved during recent years). However, there is a further sort of differentiation that, while undoubtedly distinguishing the product from others and enhancing its general appeal, leaves it truly *unchanged*.

How is it possible to create distinction without difference? It is best to illustrate this matter by referring to a simple example, taken from an advertisement published during September 1990 in a Minneapolis newspaper. The advertisement, placed by a retailing company operating a chain of department stores, promotes the sale of the chain's own brand of men's shirts. A particular feature of the advertisement is a small table (reproduced in Figure 1 below) that shows, for shirts kept in stock, the various combinations (marked by an 'x') of neck size and sleeve length. The purpose of the table is to advertise the width of the firm's product range (recently extended to fifty sizes), and thus its ability to serve a very broad spectrum of customers ("In your size and 49 others, too").

		Neck Size (inches)								
		14½	15	15½	16	16½	17	17½	18	18½
Sleeve Length (inches)	32	x	x	x	x	x	x	x		
	33	x	x	x	x	x	x	x		
	34	x	x	x	x	x	x	x	x	x
	35		x	x	x	x	x	x	x	x
	36			x	x	x	x	x	x	x
	37			x	x	x	x	x	x	x
	38					x	x	x	x	x

Figure 1. An Example of Product Differentiation

Now we may observe in this example that, although the firm is clearly seeking to distinguish itself by offering a greater breadth and choice of product, the nature of the differentiation is such that it leaves the product *per se* very much the same. For those buyers whose needs were satisfied by a neck-sleeve combination falling within the original range, the expansion to fifty sizes provides nothing that is new: the color, style, cloth, packaging and

general conditions of sale remain quite unchanged. Indeed, even for those who (owing to their bodily dimensions) were previously beyond the boundaries of the market, the product has not altered, but merely become more accessible. Yet it is undeniable that the fact of differentiation has created a real distinction between this retailer and its competitors. The question we must pose is, therefore, how has this been achieved when the product itself is no different?

The answer, of course, lies in the concept of product *variety* – the presence, within a general class of product, of multiple yet distinct variations that reflect differences in consumer characteristics and preferences. A wider variety of product implies that these differences may be more closely accommodated, to the greater satisfaction of those whose individual needs or tastes are thereby more precisely addressed. Since there is no essential change in the product itself, there is no loss of value to those buyers who were content with the original offering, for (if not inclined to adjust their purchasing habits) they may direct their custom much as before. The benefit of increased variety to the producer therefore, is that it serves to attract new customers without risking the desertion of the old.

At this point, we should perhaps note that product variety is a much broader and more pervasive phenomenon than our simple example may seem to suggest. The general notion of variety applies not only to sizes of product, but also to innumerable other features – color, style, flavor, texture, shape, packaging, etc. – as well as to the locations and times at which the product is sold. Furthermore, although we tend to think of variety in the context of current choice, it may also extend over time – that is, where multiple product variations (e.g., of fashionable clothing) are offered during a single season or year.

Returning now to the question of output measurement and productivity growth, it seems clear that the degree of variety is an important, yet entirely indirect, aspect of product value. Any increase in the prevailing extent of product variety will therefore imply a general rise in the ‘indirect service’ element of production, although a cursory examination of individual products may reveal little of the broader trend. As a result, the process of price deflation will tend to discount the economic contribution of greater variety and product choice, and measures of national output will be systematically understated – as will be the rate of productivity growth<sup>8</sup>. At the same time, as more resources are devoted to supplying the indirect services associated with a more varied and complex productive system, there will be a rise in the number of service workers, without there being any marked alteration in the composition (goods versus services) of final demand.

Is our argument valid? Clearly this depends, directly, on the answer to one central question: has there, during the past two decades, been any unusual increase in the degree of product variety, and if so, why? Product differentiation is not a new phenomenon, and output measurement has always suffered from its effects: rising levels of variety have been common for much of the present century. Why then should these circumstances have changed, so suddenly, after 1973? What evidence is there that such a change actually occurred?

These questions will be addressed in the following sections. In brief, we shall propose that recent advances in our technology of information processing, by significantly reducing the information costs associated with greater differentiation and product variety, have facilitated an extraordinary increase in the general diversity of our economic output. We shall then submit evidence to this effect, drawn from the post-war experience of the United States. Finally, we shall review the limitations of our analysis, and examine the extent to which, despite the shortcomings of current measurement procedures, the post-1973 ‘productivity slowdown’ remains a real, and profoundly disturbing, phenomenon.

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<sup>8</sup>Lancaster (1979, p. 315) draws a similar conclusion.



## Production Costs and Information Processing

In our discussion thus far, we have concentrated on the problem of product differentiation and the difficulties it creates in relation to the deflation of economic output. However, we have given rather less attention to the question of how greater differentiation and variety affect production *costs*: to a large extent, we have simply assumed that indirect costs would rise as resources are diverted to the provision of 'built-in' services. Yet for this to occur across the entire spectrum of economic activity, it seems reasonable to suppose that these costs have, for some reason, become less in relation to the additional utilities that greater variety affords. Our task now is to explain the origin and nature of this change in production costs, and to demonstrate its effects on the workings of our economic system.

Firstly, it is well known that for many industrial firms, the cost per unit of production varies according to the scale of output: in general, as the scale increases, and larger volumes are produced, so the average cost of producing each unit tends to fall. This circumstance, often described by the phrase *economies of scale*, suggests that competing firms will produce in the largest possible quantities, in order to minimize their overall unit costs. Indeed, the method of 'mass production' that emerged from the technical advances of the industrial revolution was based, to a great extent, on this very principle. The result, in terms of economic organization, has been the development of discrete industries, in which a few giant firms dominate the total process of production and distribution.

Economies of scale are not however the only force that determines the level and character of productive output. Although costs might be lower when quantities are larger, so too is the number of *different* products that can be produced, since each takes its share of a finite market. Thus, as the scale of production increases, a point is reached where the advantage of lower cost is outweighed by the demand for some measure of product differentiation and variety. Firms will not, therefore, increase their output to the competitive maximum, but will settle at a smaller scale, where the demand for a differentiated product balances, through the higher price that it commands, the somewhat higher unit costs that the firm must incur in its production.

This state of balance will not however be of any great duration, since costs may be reduced still further by combining, within the boundaries of a unified enterprise, the production of many individual firms. These additional savings arise from the fact that differentiated products, although distinct, are also in some degree related: combined production therefore allows many of the common expenses to be shared, so reducing the 'overhead' cost associated with each unit of output. These *economies of scope*, so called, describe the cost advantages of multi-product operation, when compared to a system in which differentiated production is undertaken by many single-product firms. Their consequence, clearly, is to reduce the cost penalty that is incurred when economies of scale are sacrificed in the interests of greater differentiation and variety.

Now it might seem that the benefits of scope economies would encourage a great concentration of economic activity, and the elimination of many smaller single-product firms: and to a considerable extent this has in fact occurred, as we noted earlier. However, the process of concentration is carried only so far, because the advantage of sharing productive resources among differentiated outputs is offset by another, vital factor: the need to process *information*.

Whenever resources, of any description, are shared among several different uses, it becomes necessary to collect, store, transmit and in a general sense, process, information. This need arises because resources can be shared only by dividing them, in some fashion, into parts and then allocating each part to a particular use. Information serves to maintain the association between parts and uses – an association that, being of a temporary and variable nature, makes resource-sharing economically efficient.

There are many examples from everyday life that illustrate the fundamental connection between resource-sharing and information processing. Library shelves are shared among books, which in turn are shared among readers:

its catalogue and circulation records maintain the requisite links. A telephone network is shared among subscribers, and its billing information shows the temporary associations established by each call. In the extreme, a firm may be considered as nothing more than an elaborate resource-sharing mechanism, its accounts reflecting how equity capital, borrowings and sales revenues have been shared among various productive uses.

The notion that information processing and resource-sharing are inextricably related leads naturally to a further consideration, that information processing is nothing other than the price that is paid for the improvement in economic efficiency that comes with the sharing of productive resources. It follows therefore that the extent of such sharing will be limited by the cost of the associated information activity. Where information processing is slow and costly, resources will be shared among comparatively few uses; should these costs fall however, many more will find a place.

If we now return to the question of the multi-product firm, and its ability to achieve economies of scope by combining the production of differentiated outputs, it will be clear that this ability is constrained by the information costs that accompany the combination process. Any decline in the cost of information processing tends, therefore, to loosen this constraint, leading the multi-product firm to an even broader scope of operation. Initially, this greater breadth may be reached by absorbing (via merger or acquisition) the activities of single-product firms, or those of multi-product firms of narrower scope. However, if information costs continue to fall, the opportunities for absorption will quickly diminish, and the firm will extend its scope through internal diversification (i.e., by introducing new products and further variations of established products). As this process continues, and as the general turmoil of competition becomes more pronounced, both absorption and extension will occur simultaneously, leading to (1) a concentration of production within large multi-product firms<sup>9</sup>, (2) a rapid rise in the general level of product differentiation and variety.

Here then, in this one factor – *the cost of information processing* – it seems we may have found a key to the long-standing puzzle of declining productivity growth. If we can show (1) that information costs have indeed been sharply reduced, (2) that this occurred during the years after 1973, and (3) that the reduction has been accompanied by an unusual increase in the extent of product variety, then we shall have evidence that supports our contention that the ‘productivity slowdown’ is, in part, attributable to a rise in the production of indirect (and hence unmeasured) service outputs. Before we undertake this demonstration however, it is necessary to examine why and how information costs may have fallen during the period in question.

### **Information Technology: Its Development and Economic Implications**

It is widely known that the post-war years have been a time of dramatic progress in the technology of information processing. Yet the development of technologies for this general purpose began much earlier<sup>10</sup>, and some remarkable inventions bear testimony to the fact: the telegraph (1837), the telephone (1876), wireless telegraphy (1895), radio (1906) and television (1923). Although all of these were in widespread use before the most recent era, and therefore may appear to have little bearing on the problems with which we are directly concerned, in reality they have been an integral part of the general shift toward a service-intensive economy. For this reason, it is instructive to begin by considering how the problem of information processing was addressed in these early systems.

Firstly, an important characteristic shared by all the technologies we have mentioned was the use of electricity to communicate information. This represented a departure from historical practice, since prior techniques had

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<sup>9</sup>Note that concentration will be limited by the extent of scope economies, beyond which small single-product firms will tend to dominate economic activity.

<sup>10</sup>See Beniger (1986) for a comprehensive account.

relied on sight, hearing or on the transportation of some physical object (such as paper, a messenger etc.). Although electrical methods overcame these natural constraints, and made possible the rapid transmission of information over great distances, the nature of the medium tended to define the way in which various types of information were carried. In the case of the telephone, radio and television, information was carried in *analogue* form, since the continuous waveforms associated with sound and vision could be translated directly (by 'analogy') into the electromagnetic waves used for electrical transmission. Telegraphy, however, required the communication of discrete symbols (numbers, letters etc.) rather than continuous waves: successive symbols were therefore transmitted in *digital* form, by varying the electromagnetic wave in ways that generated distinct and recognizable patterns.

Although the telegraph, and hence digital transmission, was the first technology of electrical communication, during the late nineteenth and early twentieth centuries it was rapidly overtaken by analogue devices (the telephone, etc.). Nonetheless, it led to the development of some fundamental ideas concerning efficient methods of communication using patterns, represented in most systems by sequences of binary digits, or *bits*. The notion that information could be systematically encoded in sequences of such digits, while not of any great significance to the telegraph itself, did however become invaluable in the context of another invention, whose operation relied entirely upon the concept of digital information.

In its original form, the electronic computer – as its name implies – was conceived as a machine for performing mathematical computations. Its earliest applications were of a purely numerical nature, involving complex calculations required for military and scientific purposes. However, the computer soon became a general-purpose device, capable of processing information in almost any form, owing to the purely digital character of its design. Although ostensibly functioning as an automatic calculator, in practice the computer was simply an elaborate communications network, based on the digital coding technique used for the transmission of information by electrical means.

Since its introduction (circa 1950), the technological development and universal diffusion of the electronic computer have accelerated, as it were without pause. The economic implications of this phenomenon, however, cannot be appreciated until the nature of information in general, and of digital information in particular, is properly understood. It is not our purpose here to meet this requirement in full, but before we proceed it will be valuable to return briefly to our discussion of information processing and resource sharing, in order to shed more light on their underlying relationship.

We suggested earlier that resource sharing is achieved by division – that is, by dividing the resource into parts (these being sub-divisions in space or time) and then associating each part with some determinate use. This 'association' requires an act of information, or a *logical coupling* (and, subsequently, decoupling) of two or more discrete entities. To achieve this, the entities (a part of a resource, and its associated use) must each be represented in logical form, as must be the nature of their association (e.g., its duration, cost or limitations). Each logical form, in turn, must be distinct (since the parts and uses are discrete), leading ultimately to the idea that the extent of resource sharing will be limited by (1) the supply of distinct logical forms, and (2) the cost of their coupling and decoupling.

The importance of the computer's digital *modus operandi* may now be made clear, since it is the essence of the digital method that information (such as discrete symbols) be represented by distinct logical forms - i.e., by sequences of binary digits that correspond to unique patterns of variation in the electromagnetic wave. Any device, therefore, that facilitates the generation, storage, manipulation or transmission of these sequences will increase the supply of logical forms, and likewise reduce the cost of coupling and decoupling. This will make possible not only more associations between more entities, but also more types of association: resources may thus be more finely divided among various uses, and the division may itself take more particular forms. The process

will eventually lead to more extensive and intricate resource-sharing arrangements, and so to an increasingly elaborate and complex productive system<sup>11</sup>.

We have now explained, in essence, why and how the development of the electronic computer has brought about a significant reduction in the cost of information processing, and we have linked this to our earlier argument encompassing resource-sharing, economies of scope, product differentiation and variety. A question remains, however, as to why the effects of falling information costs did not become evident during the decades *preceding* 1973 – a time when productivity growth remained strong, despite the growing use of computer technology. How can we account for this twenty-year delay?

Our answer to this question requires some preliminary explanation of the history of computer design and manufacture<sup>12</sup>. Since the computer was conceived as a digital device, it relied on electrical circuits to represent the various digits required for information encoding. In the very earliest machines, these circuits were constructed from electro-mechanical relays, but these were soon replaced by vacuum tubes, which – having no moving parts – greatly increased the speed and reliability of computation. After 1950 however, vacuum tubes were themselves replaced by solid-state transistors (miniature electrical components made from silicon) which were much smaller and lighter, and which could be manufactured in large batches (and hence at much lower cost) by means of photolithography.

As time progressed, the transistor's size and cost advantages allowed computer design to become increasingly sophisticated. This trend was reflected in the growing complexity of the underlying circuitry, which required the inter-connection of a rising number of discrete electrical components. Eventually, the high cost of assembling circuits containing hundreds of thousands of elements led to the invention (1959) of the *integrated circuit* – a complete electrical circuit etched in a minute 'chip' of silicon. During the following decade, circuits constructed from individual transistors were steadily replaced by integrated circuits, as improved design and manufacturing techniques enabled the integration of ever-greater numbers of elements.

Despite its very considerable benefits, the integrated circuit was subject to an important limitation, in that its functions were defined entirely by its physical structure. In consequence, each new application required the design and manufacture of a different circuit, implying low-volume production methods and thus a relatively high cost per circuit. As the density of integrated circuits – and hence their range of applications – gradually increased, so too did the difficulty of manufacturing a growing diversity of specialized circuits. Paradoxically, however, higher circuit densities also made possible the invention of the *micro-processor*, or 'computer on a chip' – an integrated circuit that contained all the essentials of a computer's central processing unit. Since the micro-processor could execute instructions (by manipulating sequences of binary digits), it could be manufactured *en masse* as a standard product and then be programmed to perform a variety of specialized functions.

Although the first micro-processor (the Intel 4004) was introduced during 1971, its range and capacity were sufficient only for relatively primitive applications. Some improvements were evident in its immediate successor, the 8008 (1972), but it was the 8080 model, introduced during 1973, that revealed the micro-processor's true potential. Using a micro-processor as a central processing unit, the *micro-computer* – smaller and less powerful than other computers, but much less costly – appeared during 1975 and grew rapidly in numbers, allowing much larger scales of production and so much lower unit costs. At the same time, circuit densities continued to increase, providing greater speed, capacity and functionality. The combined effect of these two trends (larger volumes and higher densities) was a steep and sustained decline in overall information costs – a decline that continues to the present day.

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<sup>11</sup>Pulley & Braunstein (1984) provide an example of this process.

<sup>12</sup>Our account is drawn largely from Braun & Macdonald (1978), and Dertouzos & Moses (1979).

Reflecting once more on the question of economic growth, it may seem almost incredible that a minute device, smaller than a fingernail, could have initiated the chain of events we have been at pains to describe. However, the true significance of the micro-processor lay not in its size, nor indeed in its actual function, but in its demonstration of the efficiency of the underlying fabrication process. Before the era of large-scale circuit integration, computer production required the manufacture and assembly of many individual components (whether vacuum tubes, transistors or integrated circuits); after 1970, methods of mass production could be used to produce multi-purpose components, suitable for many applications and for many types of computer system. This was true not only for the processing units used in micro-computers, but for many other kinds of circuit (such as those used in computer memories) that relied on large-scale integration techniques to achieve the economic benefits of mass production.

We have now completed our analysis of the computer's effect on the cost of information processing, and have explained, by reviewing the computer's technological evolution, why this effect became noticeable after 1973, rather than before. By so doing, we have developed in full our explanation of the recent decline in America's rate of productivity growth, and of the manner in which this decline is associated with the growing use of information technology. Furthermore, from the generality of our reasoning it is but a short step to conclude that the same phenomenon will be found, not only in the United States, but in all nations that have taken advantage of the new technology. At this stage, then, it remains but to be shown that the record of history supports our interpretation of the case, and that matters do indeed stand as we have presented them. To this purpose, we shall now bring forward evidence that, while not constituting final proof, yet gives substance to the logic of our general argument.

### III. WEIGHING THE EVIDENCE: THE UNITED STATES, 1950 – 1989

Although we have dealt with the subject at some length, our explanation of the 'productivity paradox' is in fact remarkably simple. We propose that recent (post-1973) advances in computer technology have greatly reduced the cost of information processing, so providing economies of scope that have stimulated greater product differentiation and variety. Since variety and choice are provided as indirect services, their contribution to output is discounted by current methods of price deflation, leading to a decline in the *measured* rate of productivity growth.

This brief summary suggests that, if we are to demonstrate the validity of our analysis, we must focus our attention on the behavior, pre- and post-1973, of three key variables: (1) the cost of information processing, (2) the level of product differentiation, and (3) the rate of productivity growth. Furthermore, we should expect these variables to be inversely related, in that falling information costs should be followed by a rising level of product differentiation and by a falling rate of productivity growth. The diagram shown in Figure 2 illustrates the essentials of this reasoning.



Figure 2. Logical Variables and Relations

Although Figure 2 clearly represents the logical structure of our argument, it is not ideally suited to empirical investigation, and for this reason has been modified as follows. Firstly, the 'cost of information processing' is replaced by the 'adoption of information technology', reflecting the supposition that the use of information technology will rise to the extent that it reduces information processing costs: the virtue of this exchange being the more tangible nature of the variable. Secondly, in the interests of consistency, each variable is expressed as a *rate of change*, causing the first variable to become the 'rate of information technology adoption', and the second, the 'rate of product differentiation'. For a similar reason, the 'rate of productivity growth' (the proportional change in output per unit of input, from one period to the next) is replaced by the 'rate of productivity' (the rate of output per unit of input, during a given period).

The result of these modifications is shown in Figure 3 below. In brief, the figure suggests that any increase in the rate of information-technology adoption will be accompanied by an increase (+) in the rate of product differentiation, and a corresponding fall (–) in the rate of productivity. Furthermore, although this is not shown in the figure, we should expect these changes to occur after 1973, rather than before.

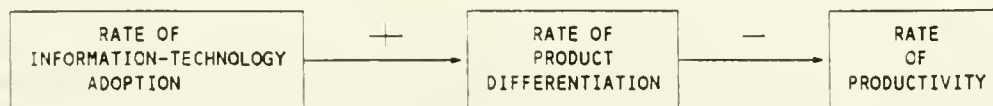


Figure 3. Empirical Variables and Relations

We shall now present, in summary form, the methods that were used to evaluate the system of relations shown in Figure 3.

## The Research Methodology

Firstly, the general approach was econometric in nature, involving the collection and analysis of time-series data for each of the three variables, across six sectors of the United States' economy. The sectors were chosen from those defined by the Bureau of Economic Analysis (BEA) following the Standard Industrial Classification, and used by the Bureau of Labor Statistics (BLS) for the purposes of reporting national productivity statistics. In this scheme, the largest economic aggregate is the *private business sector* (some 77% of 1987 Gross National Product, or GNP), this being in turn sub-divided into a *goods-producing sector* (27% of GNP) and a *services-providing sector* (50% of GNP). The goods and services sectors are themselves sub-divided into industries, but owing to inconsistencies in the data sources, the analysis included only three industries (*finance, insurance and real estate; communications; transportation*) within the services sector. Figure 4 illustrates the relationships between the various economic sectors.

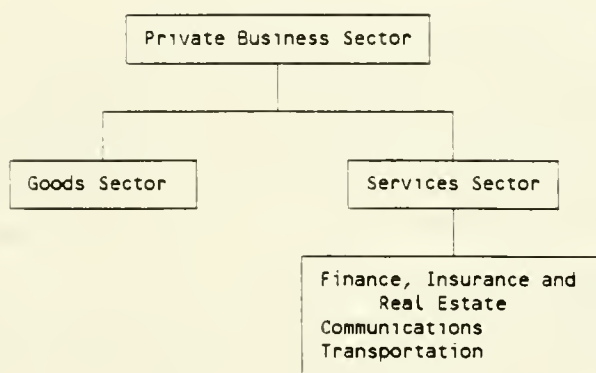


Figure 4. Hierarchy of Economic Sectors

Within each of the six sectors, the data for each variable consisted of forty annual observations covering the period from 1950 to 1989. For consistency, and to eliminate the effects of population growth, changing habits etc., the divisor (hours at work) in the productivity variable was applied to each of the other two variables. In effect, therefore, for each sector the data set comprised measures of (1) the rate of information-technology adoption, (2) the rate of product differentiation, (3) the rate of output, and (4) hours at work.

We now turn to the process of data collection. The data relating to the rate of information-technology adoption were taken from the *BEA Industry Investment Data Tape*, a standard computer tape that provides a breakdown of the United States' capital investment by (1) industry of ownership and (2) type of capital. In the main, information-technology capital is classified either as 'communication equipment' or as 'office, computing and accounting machines' (OCAM), but since the former type is concentrated in the communications industry and is used to provide a service (e.g., telephony) to other 'adopting' industries, the analysis included only the latter type (OCAM).

Regarding the use of the OCAM investment data, there are two difficulties that deserve mention. Firstly, since the data are classified by industry of ownership, rather than by industry of use, many distortions have been introduced by the growing popularity of computer leasing (which increased, as a proportion of total computer investment, from less than 10% in 1982 to more than 40% in 1989<sup>13</sup>). Computer leasing is a complex phenomenon, and we found no method of correcting these distortions: note however that the effects of leasing activity are significant only during the final years of the period, and are less marked at higher levels of analysis.

Secondly, the OCAM data represent monetary values, not physical quantities, and are given in both historical (current) dollars and constant (1982 base) dollars. At first glance it might seem preferable to use the constant-dollar series, which removes the effects of price inflation and hence reflects the 'true' level of capital investment. In the case of OCAM, however, since 1985 the BEA has used an *hedonic* price index for deriving the constant-dollar estimates, and the post-1982 advances in computer technology have caused these estimates to diverge very widely from the current-dollar figures. For example, in 1989, when total current-dollar OCAM investment was \$45 billion, the 'constant-dollar' equivalent was \$125 billion. For this reason, the current-dollar series (with general inflation representing a nominal 'technical change' component) was used to represent the rate of information-technology adoption.

Our second variable, the rate of product differentiation, was represented by the annual number of applications for trademark registration submitted to the United States' Patent and Trademark Office (PTO). Although not all forms of product differentiation are associated with formal trademarking, a measure of this nature does encompass those that are of a more general economic significance. Trademarks have several further advantages, since they are widely used to distinguish all kinds of goods and services, reflect actual commercial and trading activity, and have been (since the Lanham Act of 1946) a standard, stable feature of the economic system. Again however, certain difficulties were evident, and these merit some brief discussion.

Firstly, there were two reasons why trademark *applications*, rather than registrations, were used to represent the differentiation variable: (1) there is a considerable delay – as much as four years – between the filing of a trademark application and its eventual registration; (2) the number of trademarks registered in any year depends very largely on the PTO's budgetary and staffing position, which fluctuates according to the level of funding provided by the federal government. Secondly, although data relating to the more recent years of our study period (1975 and later) could be obtained directly from the PTO, for the earlier years it was necessary to derive supplementary data from *The Trademark Register of the United States*. Thirdly, we should note that the 1946 Act required marks to be 'used in commerce' before an application for registration would be considered by the PTO; from 16th November, 1989 the Trademark Revision Act of 1988 allowed the PTO to accept applications where only an 'intent to use' is expressed (resulting in a surge of applications and hence a slight upward bias in our data for 1989).

Data relating to the rate of productivity (the third variable in the schema shown in Figure 3) were derived from the standard BLS estimates, which are based on the BEA's analysis of GNP by 2-digit SIC industry. Note that the BLS provides estimates of both output and (independently, from its own sources) hours at work. It should also be noted that, since government activities were excluded from the other data sets (i.e. from those relating to information-technology adoption and product differentiation), the output and hours of fee-for-service government enterprises were subtracted from the corresponding (output and hours) figures for the 'private business' and 'services-providing' sectors.

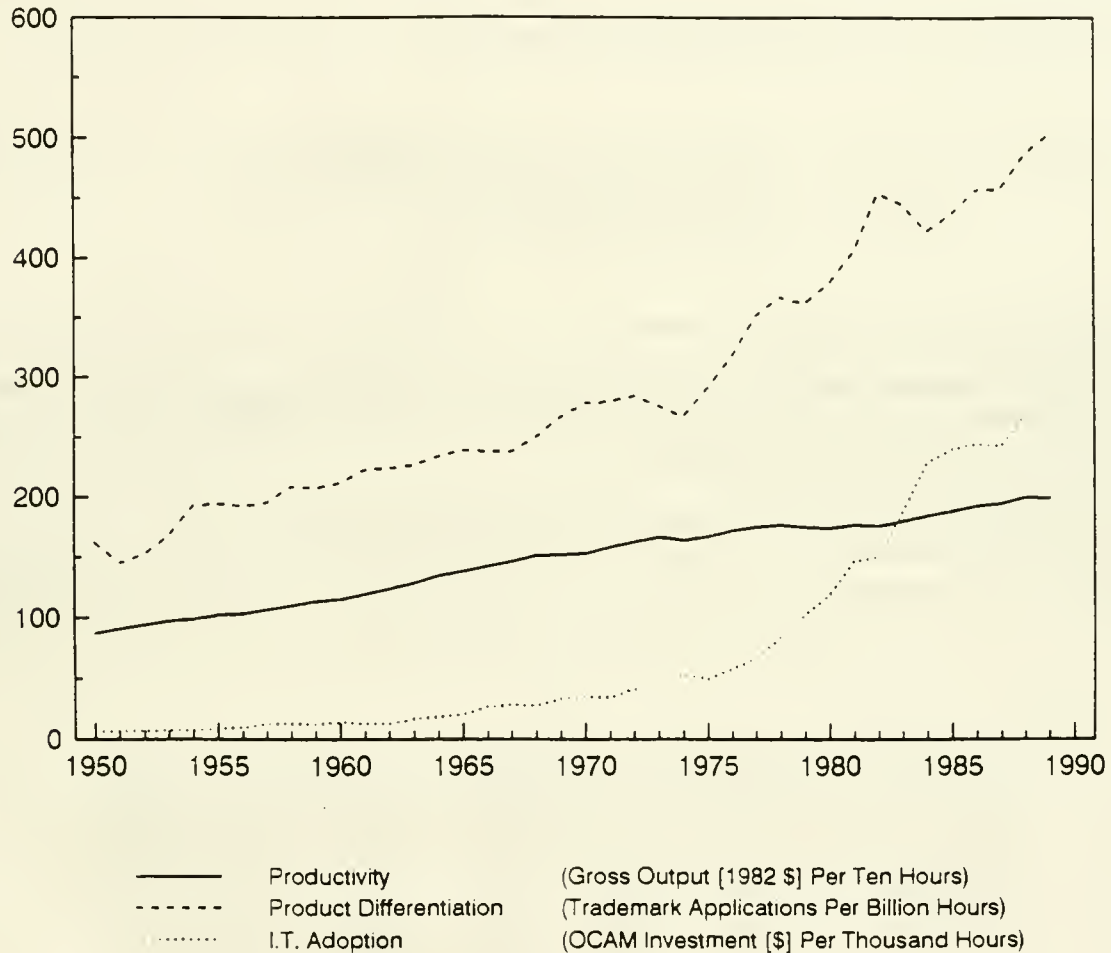
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<sup>13</sup>These figures are derived from surveys conducted by the Computer Dealers and Lessors Association, Inc.



## Data Analysis and Results

After collection, the data were analyzed both graphically and statistically. In the interests of brevity, and because the analysis revealed very similar patterns in each of the economic sectors, only the most general results (those for the *private business* sector) will be presented here. To this end, Figure 5 shows, for the private business sector, the forty-year trends (scale-adjusted) in each of the three variables.



**Figure 5. Information Technology, Product Differentiation and Productivity:  
Private Business Sector, 1950 – 1989**

Referring to Figure 5, the interactions between the three time-series reflect, very closely, the set of relationships implied by the schema of Figure 3. Taken broadly, the period between 1950 and 1973 is one of rapid productivity growth, accompanied by relatively slow growth in product differentiation and information-technology adoption. After 1973 however, the situation is completely reversed, there being clear evidence of slowing productivity growth and a sudden acceleration in both information-technology adoption and product differentiation.

The statistical significance of the trends shown in Figure 5 was tested by estimating the parameters of the following econometric model:

$$D_t = \alpha_1 + \alpha_2 t + \alpha_3 I_t - u_{1t} \quad (1)$$

$$P_t = \beta_1 + \beta_2 t + \beta_3 D_t - u_{2t} \quad (2)$$

where  $\alpha$  and  $\beta$  represent the structural parameters of the model,  $t = 0, 1, 2, \dots, 40$  (i.e.,  $t =$  calendar year - 1950) and:

$$\begin{aligned} D_t &= \text{rate of product differentiation in year } t \\ I_t &= \text{rate of information-technology adoption in year } t \\ P_t &= \text{rate of productivity in year } t \\ u_{nt} &= \text{random error in year } t \quad (n = 1, 2). \end{aligned}$$

In equation (1), the rate of product differentiation  $D_t$  is represented as a linear function of time  $t$  and the rate of information-technology adoption  $I_t$  with a random error component  $u_{1t}$ . In equation (2), the rate of productivity  $P_t$  is likewise a linear function of time  $t$  and the rate of product differentiation  $D_t$ . The time trend  $t$  serves to remove the effect of any common upward drift over time, and thus concentrates the analysis on differential fluctuations around a linear trend.

The estimation procedure was based on the two-stage least-squares regression technique, the two equations in the model being subject to joint estimation. To counter the effects of autocorrelation, each of the dependent variables  $D_t$  and  $P_t$  was specified as a second-order autoregressive process. The results are shown in Figure 6.

SECTOR	EQN.	d STAT.	PARM.	ESTIMATE	STD. ERR.	t STAT.	P-VALUE
Private Business	1	1.894	$\alpha_1$	152.355	6.934	21.97	0.0001 *
			$\alpha_2$	5.272	0.542	9.73	0.0001 *
			$\alpha_3$	0.503	0.076	6.63	0.0001 *
	2	1.912	$\beta_1$	11.253	0.277	40.69	0.0001 *
			$\beta_2$	0.443	0.018	24.64	0.0001 *
			$\beta_3$	-0.018	0.002	-8.62	0.0001 *

**Notes.** (1) \* indicates that the estimate is significant at  $\alpha = 0.05$   
 (2) Lower and upper bounds for the Durbin-Watson d statistic:

$$\begin{aligned} d_L &= 1.26, & d_U &= 1.72 & (\alpha &= 0.05) \\ d_L &= 1.07, & d_U &= 1.52 & (\alpha &= 0.01) \end{aligned}$$

**Figure 6. Parameter Estimates: Full-Period Model**

The results shown in Figure 6 clearly support the implications derived from the graphical analysis. The estimates of parameter  $\alpha_3$  indicate a significantly positive relationship between the rate of information-technology adoption and the rate of product differentiation; likewise, the estimates of parameter  $\beta_3$  indicate a significantly negative relationship between the rate of product differentiation and the rate of productivity. However, these are general relationships that hold over the whole study period: in order to evaluate the significance of changes between the pre-1973 and post-1973 periods, the analysis was refined by specifying an inter-period model:

$$D_t = \alpha_1 + \alpha_2 t + \alpha_3 I_t + \alpha_4 (I_t - I_{23}) X_t + u_{3t} \quad (3)$$

$$P_t = \beta_1 + \beta_2 t + \beta_3 D_t + \beta_4 (D_t - D_{23}) X_t + u_{4t} \quad (4)$$

The notation in these modified equations is the same as that in equations (1) and (2) above, except that:

$$\begin{aligned} I_{23} &= \text{rate of information-technology adoption in year 23 (1973)} \\ D_{23} &= \text{rate of product differentiation in year 23 (1973)} \\ X_t &= 1 \text{ if } t > 23 \\ &= 0 \text{ otherwise.} \end{aligned}$$

The dummy variable  $X_t$  serves to separate the differential effect of the rate of information-technology adoption  $I_t$  on the rate of product differentiation  $D_t$  into two separate components: a first-period component,  $\alpha_3$  and a second-period component ( $\alpha_3 + \alpha_4$ ). The parameter  $\alpha_4$  therefore represents the change in the differential effect between the first and second periods. Likewise, the parameter  $\beta_4$  represents the inter-period change in the differential effect of the rate of product differentiation  $D_t$  on the rate of productivity  $P_t$ . Note that in other respects, the analytical structure and estimation procedure were the same for both the full-period and inter-period models.

The estimates of the parameters of the inter-period model are shown in Figure 7.

SECTOR	EQN.	d STAT.	PARAM.	ESTIMATE	STD. ERR.	t STAT.	P-VALUE
Private Business	3	1.839	$\alpha_1$	152.496	7.078	21.54	0.0001 *
			$\alpha_2$	6.399	1.587	4.03	0.0003 *
			$\alpha_3$	-0.165	0.894	-0.18	0.8549
			$\alpha_4$	0.616	0.823	0.75	0.4594
	4	1.931	$\beta_1$	7.953	1.463	5.44	0.0001 *
			$\beta_2$	0.328	0.049	6.74	0.0001 *
			$\beta_3$	0.003	0.009	0.36	0.7212
			$\beta_4$	-0.012	0.006	-2.12	0.0414 *

Notes. (1) \* indicates that the estimate is significant at  $\alpha = 0.05$

(2) Lower and upper bounds for the Durbin-Watson d statistic:

$$\begin{aligned} d_L &= 1.21, & d_U &= 1.79 & (\alpha &= 0.05) \\ d_L &= 1.02, & d_U &= 1.58 & (\alpha &= 0.01) \end{aligned}$$

Figure 7. Parameter Estimates: Inter-Period Model

The results shown in Figure 7 reveal no significant post-1973 change ( $\alpha_4$ ), in the relationship between the rate of information-technology adoption and the rate of product differentiation: this is entirely consistent with our theoretical position, which suggests a constant positive association between these two variables. On the other hand, after 1973 there is clearly a significant negative change ( $\beta_4$ ) in the relationship between the rate of product differentiation and the rate of productivity, implying that the generally negative association between these variables, although of no significance ( $\beta_3$ ) during the early years (when the rate of differentiation was probably too low to have any noticeable affect on productivity growth), suddenly intensified after 1973, supporting our argument that the productivity slowdown of the past two decades is due to an unusual acceleration in the degree of product differentiation and variety.

#### IV. CONCLUSION

Taken as a whole, the empirical evidence lends some plausibility to our interpretation of America's recent economic history, and to our assertion that the post-1973 decline in productivity growth may be traced to a rise in the production of indirect (and thus unmeasured) service outputs. We should note however that our empirical analysis does not indicate *how much* of the total decline may be attributed to this change in the composition of the national product: we have merely demonstrated that *some* influence seems to be present. Clearly, a more conclusive analysis would require the inclusion of other variables (such as energy prices, labor quality etc.) that have also taken their toll.

Although the scope of our investigation is thus somewhat narrow and open to question, we would propose that a more important issue is its meaning and economic implications. In our original discussion of the problem, we suggested that the decelerating growth rate reflects an underlying weakness, and is not solely the product of inadequate measurement and statistical oversight. Yet, to this point, we have argued that slower productivity growth is indeed the consequence of a failure to account for the intangible benefits of greater variety and freedom of choice. What then is the nature of this 'underlying weakness', and how is it related to the hypothesis that our measurement procedures ignore the contribution of indirect services ?

The answer to this question is that indirect services may be provided with greater or lesser efficiency, and that the American economic system is comparatively ill-suited to this new form of productive endeavor. It is this circumstance that explains why, quite apart from any *historical* changes in its productivity record (with which we have thus far been concerned), the United States' economic performance has not matched that of its international rivals, *even during the pre-1973 period of 'rapid' productivity growth*<sup>14</sup>. In this respect, the 'productivity slowdown' of the past two decades represents, not merely an accounting failure, but a real deterioration in long-run productive efficiency.

The basis of this ominous claim, and its implications for economic policy, will be the subject of future work. Clearly, there can be no retreat from the 'information society' and its technological methods of production: our quest must be to understand how these methods might have altered our canon of economic efficiency. A revision of such precepts may entail a transition to new forms of enterprise, to new ways of organizing economic activity, and perhaps to new public institutions – better suited, we may hope, to the challenges of the coming century.

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<sup>14</sup>Baumol, Blackman & Wolff (1989, p. 88) illustrate the magnitude of this shortfall during the period 1950 – 1979.

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