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AND

ECONOMIC PRODUCTIVITY

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Center for Information Systems Research

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This paper analyzes the role of information resources in the development of the United States economy and especially in the determination of productivity levels. The analysis is based on a formal economic model of the interrelationship between two sectors: an information sector, comprising all labor and capital used to process and handle information, and a production sector, which processes and handles material goods. The purposes of the model are to explain the past growth of the information sector workforce, to identify productivity trends in the sector, and to determine the implications of those trends for future economic performance. The analysis shows that, historically, the rate of efficiency improvement in information handling (essentially white-collar) work has been much slower than in production work. However this pattern is changing rapidly, chiefly as a result of the introduction of new data processing, communication and storage technologies. Our model shows that the expected future level of investment in these information technologies will be sufficient to reverse, by the mid 1980s, the slowdown of economic growth which is currently afflicting industrialized countries.

Keywords. Information economics, productivity, information technology, information sector, communication economics, white-collar productivity, office productivity, office automation, economic growth.

1. Introduction

The pattern of development of industrialized countries is being affected by two important trends which have only recently attracted the attention of the economics profession. Both concern the allocation of resources to information handling: to the creation and processing of knowledge or symbols rather than physical goods or material services. The first trend is the growth in demand for these information handling activities. For reasons which we analyze later in this paper, economies throughout the world are requiring an increasing volume of information resources. The measure most commonly used to assess this trend is the proportion of white-collar or non-production workers in the labor force. These workers can be defined to constitute an information sector of the economy, comprising such activities as management, administration, clerical work, accounting, brokerage, advertising, banking, education, research and other professional services. Its counterpart we term the production sector: factory, construction, transportation, mining and agricultural activities. Studies show that about half of all economic activity in the United States is accounted for by information creation and processing, and that the proportion

*I am grateful to Michael Tyler for discussions and contributions to many of the ideas arising in this paper.

has been rising through time; it was less than 18% in the year 1900.[1] This shift of resources from the traditional productive activities of industrial and agricultural workers to primarily office-based information handling functions constitutes one of the most striking changes to have taken place in the economy over the course of this century.

The second trend is the emergence of new information technologies. Recent advances in electronic memory, processing and transmission devices have brought down the cost per unit performance of elementary data handling functions by some orders of magnitude during the last two decades, and these cost trends show every sign of continuing. Computing, telecommunications and office automation systems based on these devices are beginning to transform the nature of information management throughout the economy.

This paper analyzes these trends and assesses their implications for future improvements in economic performance. The division of the economy on which this study is based, namely that between information handling and goods handling processes, is unconventional. We give in the following paragraphs a brief overview of the nature of this distinction and its importance in understanding productivity growth.[2] The statements made below are examined and justified in more detail in the body of the paper.

The economic problem facing a society can be said to have two components: there is a *production task*, that of producing goods and services using the limited labor and material resources available, and there is an *information handling task*, that of managing, organizing, coordinating and developing the many individual productive activities. The magnitudes of the production and information sectors reflect the resource requirements of these two aspects of the economic problem and vary systematically with the level of industrial development.

Historically, the production task was dominant. The great majority of the population was engaged in the production side of the economic process, where it was the efficiency of industrial and agricultural processes which determined levels of output and hence of national prosperity. The resources required to organize and coordinate the production activities were relatively small, so a certain amount of inefficiency or wastage in the information sector did not have a major influence on overall economic efficiency.

Such had been the importance of the production problem that, rightly, the great majority of inventive and research effort in the past two or more centuries had been directed towards increasing industrial rather than information handling productivity. Consequently, vast gains in technical efficiency were achieved. The quantities of labor required in the industrialized countries to produce food, clothing, means of transport and the basic requirements of our societies have been reduced greatly during the nineteenth and twentieth centuries. Agricul-

[1] Fritz Machlup (1962) was the first to measure the extent of resources allocated to the creation and processing of knowledge as opposed to other kinds of products. Studies of a similar kind have subsequently been carried out in the United States by Peter Drucker (1968), Daniel Bell (1973), Marc Porat (1977), and again by Machlup (1980). The identification of information handling activities as a distinct sector is due to Porat. Studies in several other industrialized countries [Organization for Economic Cooperation and Development (1981)] confirm a similar pattern of growth in their information sectors.

[2] See also Lamberton (1982) for a discussion of the implications of information sector measurement for economic analysis.

ture provides perhaps the most important and clearest example: traditionally food production has consumed the majority of the working effort of man, while now less than 4% of the workforce of the Unites States produces more than enough for the needs of the country.[3]

Our data show that by the middle of the twentieth century the information handling task had grown in the United States to the point where it was consuming about one third of all economic resources; the fraction has since risen to about one half. Technological developments in the production sector were having increasingly less effect on overall output as the proportions of production to information labor fell. The largest untapped opportunities for improving economic performance lay in the area of information handling. Consequently large research and development resources began to be directed to the creation of technologies which process, store, transport and manipulate information. These include computers, telecommunications systems, electronic data bases, word processors and a wide range of other data handling equipment.

To understand developments in the information sector and their future effects on economic performance, we require a model of the interrelationship between information resource use and economic productivity. The findings reported in this paper are based on such a model; the mathematical details are given in the appendix. The model shows that growth in the information workforce has been caused primarily by differential rates of technological progress in the production and information sectors. As industrial technology develops, the processes of production leading to the final output of goods and services in the economy become more complex. The organizational or informational task of coordinating the diverse steps in the production chain grows, as the number of transactions within and among productive units increases. Since the functions of information handling have not benefited from comparable efficiency improvements, the number of information workers must grow in response to this increasing organizational task. However, as industrial efficiency growth begins to decline and information handling productivity increases, the size of the information sector can stabilize or even contract. We use this model both to explain the historic growth in the United States information workforce and to predict changes in its size during the next decade and a half.

Our analysis of the productivity growth patterns of the two sectors shows that, historically, the rate of technological progress in white-collar functions has been much lower than in production work. However, the productivity of the information sector is beginning to rise rapidly, chiefly as a result of investment in the new technologies. This increase will tend to counteract the effect of stagnating performance in industrial occupations.[4] Indeed we show that on current trends information technology investments will reverse, by the mid 1980s, the slowdown in economic growth which began to afflict industrialized countries in the last decade.

[3]It is indicative of the extent of the 'information revolution' that the United States now spends less on food production than on the operation of its telecommunications networks [Jonscher (1981)].

[4]This point has been noted by Tyler (1981), who presents a number of case studies illustrating the opportunity for enhancing productivity through the adoption of new technology in white-collar environments. Tyler's paper also advances the hypothesis that information sector growth and falling productivity growth are causally interrelated.

2. What does the information sector do?

The number of different information handling functions carried out in a modern economy is clearly vast, and any modelling work in this area must involve considerable simplifications. In this section we present a framework which allows us to distinguish and measure several major classes of information activity which are relevant to a study of economic growth.

We define two sectors of the economy:

(1) An information sector, comprising the activity of all individuals whose primary function is to create, process and handle information.
(2) A production sector, comprising the activity of all individuals whose primary function is to create, process and handle physical goods.

The defining characteristic is the nature of the *output* produced by each individual (together with the capital equipment or tools associated with his or her work). If the output has value because of its information content – as in a memorandum, decision, financial document, lecture or research report – then the activity is assigned to the information sector. The extent to which information is used as an *input* to the task is not an issue; all tasks require some knowledge in their execution.

Identifying the pattern of expenditures on information activities is made possible by the very high degree of occupational specialization present in modern societies. We use occupational categories as the primary instrument for distinguishing between information and production functions. If a person is classified in the labor statistics as a billing clerk, we may be reasonably confident that his or her primary functions are to prepare and process bills; these are information handling activities and consequently the billing clerk is assigned to that sector. Conversely, if a person is classified as a sheet metal worker his principal output is worked metal and not information; we therefore classify him in the production sector. Occasionally, the billing clerk may help to unload a delivery truck (production, not information handling), and the sheet metal worker may fill out timesheets (information handling, not production); but these activities are the exception rather than the rule.

A few worker types are more difficult to classify; in these cases we have to make a (sometimes rather arbitrary) choice. Foremen, for example, spend some of their time administering and some carrying out the same work as their subordinates. The introduction of automated factory equipment is blurring even the conceptual distinction between information and production sector activities.[5] Fortunately for our purposes, the number of occupations for which classification problems of this kind arise is a small proportion of the total. The great majority, perhaps 95%, of the working population can be identified with confidence as fitting one or other category.

[5] Is the function of operators in a modern automated assembly line to press buttons (information handling), or to assemble the items on the line (production)? Clearly this depends on whether we draw the boundary around each worker's activity to include or exclude the machinery associated with his function. This example demonstrates that the definition and measurement of the information sector depend ultimately on the way in which economic activity is subdivided into individual analytic units (see appendix).

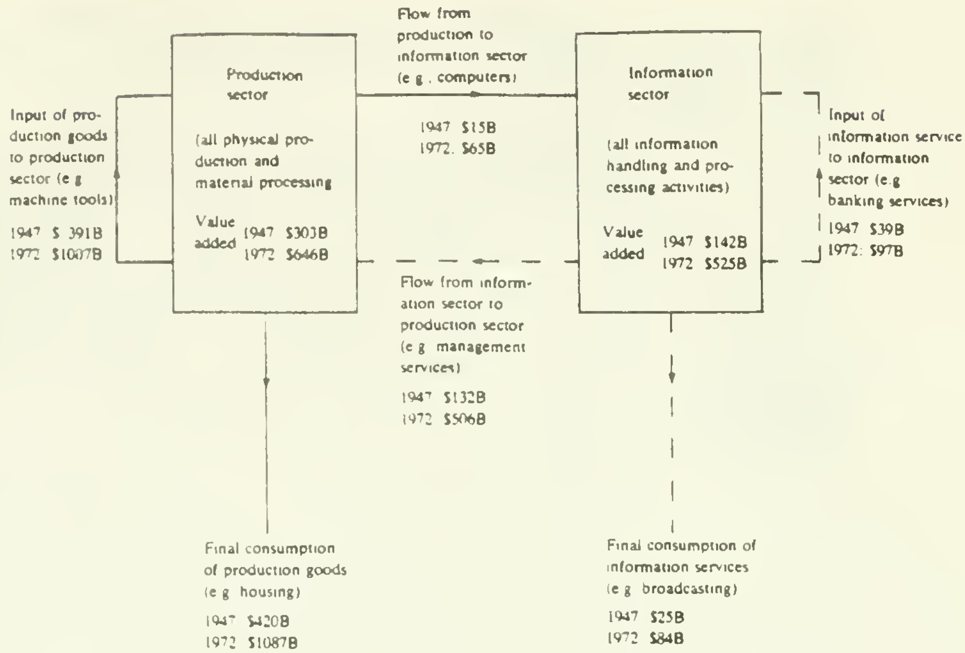

Fig. 1. Schematic representation of the production and information sectors of the economy, with examples of flows of goods and services [data refer to United States economy, and indicate values of flows of goods and services in constant (1972) dollars].

Fig. 1 contains a schematic representation of the relevant components of the economy. The boxes on the left and right represent the production sector (all physical production or material processing operations) and the information sector (all information handling and processing operations) respectively. The solid lines represent the output of the production sector, the broken lines the output of the information sector. In each case the output is divided three ways: part goes to final consumption, part is used as input to the same sector, and part is used as input to the other sector. One example of each of these flows of goods and services is marked on the diagram.

The magnitudes of each of these flows have been calculated for two years, 1947, and 1972. Details of the method by which each intersectoral and intrasectoral flow is identified and measured are contained in another paper [Jonscher (1982b)]. The results are marked on fig. 1.

Three features of the data stand out. The first, already well established, is that the information sector has been growing much more rapidly than the production sector. The growth rate of the former has been almost double that of the latter: information sector value added increased by a factor of about 3.7 (in constant value dollars) between 1947 and 1972, while production sector value added grew by a factor of just over 2. The second feature is that the output of the information sector is used primarily by industry rather than directly by consumers. Whereas final consumption of such information items as the media and printed matter had reached $84 billion by 1972, this figure is dwarfed by the $506 billion flow of information sector services required by the production sector. Thirdly, the single flow in this input–output structure which has grown at the most rapid rate has been the input of goods to support the information sector – goods such as office technology and facilities. This grew by a factor of more than 4 between 1947 and 1972, from $15 billion to $65 billion at 1972 values. The implications for the future performance of the information sector are discussed later.

Having established the status of the information sector as an input to the production and consumption needs of the economy, we require a more detailed characterization of the types of functions performed within that sector. Fig. 2 contains the results of a breakdown of information activity by functional category. The categories are listed on the left-hand side of the figure, and the percentages of the information sector workforce falling within each are shown in the center. The data are based on an allocation of occupations to functions at the most detailed level of occupational definitions published by the Bureau of Labor Statistics. Actual figures are given for the year 1978 and forecasts, based on Bureau of Labor Statistics projections, for 1990.

The categories have been chosen to allow us to distinguish among the major functional roles performed by the information sector. The first distinction we wish to make is that between work which contributes to the long term or capital stock of knowledge, and that which is concerned with the coordination and management of current economic activity. Research and development, education and training, and creative professional work such as writing, are the major activities constituting the former category. The latter includes such functions as management, accounting, buying, selling and brokerage; these cover the actions of enquiring, directing, monitoring and recording which accompany and serve to organize economic production. The two groups are shown bracketed on the right-hand side of fig. 2. It is clear that the great majority of information workers, some 81%, fall into the latter group, being concerned with current information management and coordination rather than contributing to the capital stock of knowledge.

Further distinctions among categories of information functions can also usefully be made. Within the broad class of activity which serves to organize and manage the economic system, we can differentiate between that which is market-based and that which occurs within hierarchical management structures such as firms or government bodies. Marketing, sales, brokerage, purchasing and much of the financial accounting function are concerned with coordinating the interaction of buyers and sellers in the marketplace, while general managers, foremen and administrators direct activity within centrally organized units. The distinction is quite fundamental, in that the extent to which economic management is centralized or left to the interaction of independent trading parties lies at the heart of the distinction between market and non-market allocation processes, and indeed between socialist and capitalist economies. It is difficult to ascertain precisely the relative magnitudes of information sector effort accounted for by the market as opposed to centralized mode of management. However the data in fig. 2 suggest that, in the case of the United States economy, these two magnitudes are very roughly similar; each amounts to somewhere in the region of half of the 80% of information sector effort which is concerned with economic management and coordination.[6] In a less market-oriented economy those proportions can be expected to differ, a larger part of the total being accounted for by centralized management and planning. What balance between these two modes of information management

[6]See footnote, page 19

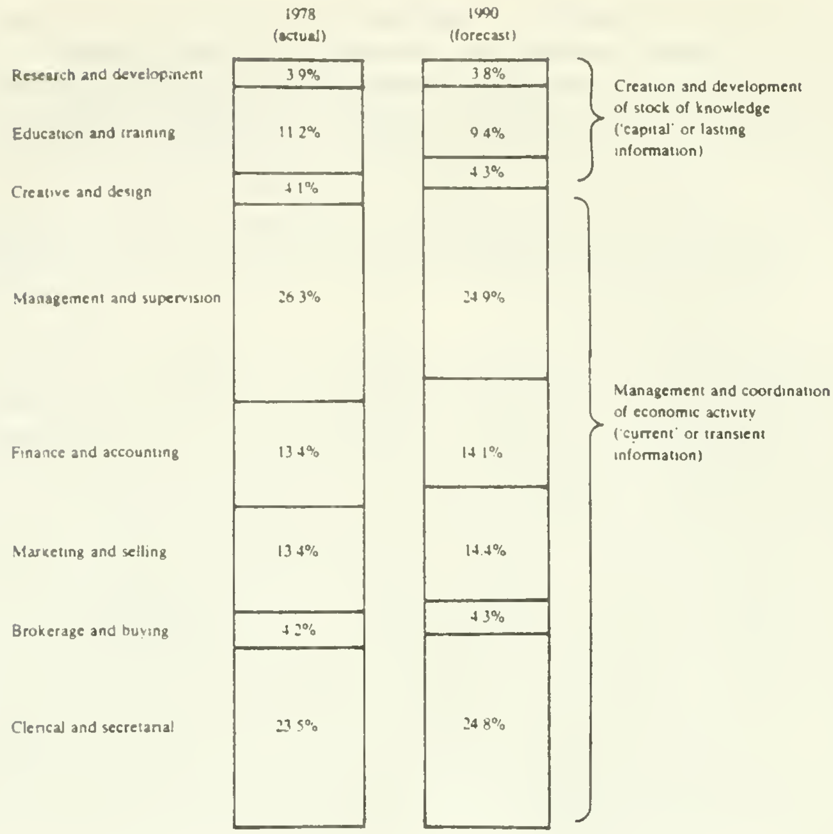

Fig. 2. Breakdown of the United States information workforce by function, 1978 and 1990 (data give numbers of workers in each category as a percentage of the information workforce. 1990 figures are based on Bureau of Labor Statistics forecasts).

leads to the most efficient organization of an economy is of course a subject of great controversy.

3. The causes of information sector growth: The competing theories

Several hypotheses have been put forward to account for the observed growth in white-collar or information-handling tasks at the expense of production activity. Among the popular explanations are:

(i) that the size of the information workforce is being swelled by increases in the number of scientific and technical personnel.

[7]This result has been derived on the basis of a detailed breakdown of the occupational definitions which make up the eight functional groups listed in fig. 1. We can indicate broadly how this result is obtained by reference to the data in the figure. The 31% of information workers (1978 data) in the categories labelled 'Brokerage and Buying', 'Marketing and Selling', and Finance and Accounting' are mostly concerned with market interactions, while the 26% classed as 'Management and Supervision' are largely responsible for controlling operations within business units. Clerical and secretarial staff are allocated approximately two-thirds to management and one-third to the other groups. The resulting overall percentages, 39% in market-based functions and 42% in hierarchical management, are of comparable size. We emphasize that this calculation is only intended to give a very approximate guide to the magnitudes involved.

(ii) that the pattern of consumption expenditures by households has changed in favor of information-related goods and services such as television, entertainment, print media, educational services and books, and
(iii) that the government, largely an information-handling organization, has grown relative to the economy as a whole.

We can use our analysis of the structure of the information sector, as discussed in the previous section, to evaluate each of these explanations. We take each in turn.

(*i*) *Growth of scientific and technical occupations.* In his description of the emergence of 'post-industrial-societies' Daniel Bell (1973) emphasizes the role of scientific and technical knowledge as a central feature of the emerging information-based economies. Bell is among several authors who draw attention in their writings to the growing number of individuals who are responsible for creating and disseminating technological information. The growth in the education sector is often linked to this phenomenon; the demand for intellectual training increases with the level of technical progress in the economy. While the trends Bell identifies are certainly present, they do not account for the general phenomenon of information workforce expansion. We note from fig. 2 that personnel in education, research and development activities account for only about 15% of the information workforce. Time trend data show that this proportion has in fact been *falling* during the past three decades [see Jonscher (1982a)], and that it will continue to fall slightly in the period to 1990.

(*ii*) *Increasing final consumption of information services.* The level of final consumption of information services has been increasing rapidly in absolute terms, but only very slowly as a proportion of total consumption. Fig. 1 shows that the percentage of consumption expenditure accounted for by the information sector grew by only about $1\frac{1}{2}$ points in the period 1942–1972, from 5.6% to 7.2%. The fraction of total information sector output accounted for by final consumption actually fell over this period, from 12.8% in 1942 to 12.2% in 1972. The change in input–output structure which was responsible for the great majority of information sector growth between these years was the increase in information service input to the production sector. This rose from $132 billion in 1947 to $506 billion in 1972, an increase of nearly 4-fold (in real terms, since all data are quoted in constant 1972 dollars).

(*iii*) *Growth of government.* The data presented in this paper do not distinguish explicitly between government and other employees. However, the number of administrative staff in Federal, State and Local Government amounts to less than 10% of the information workforce. Although this proportion has been growing slowly during the last few decades, the growth of the information workforce must still be reckoned as predominantly a private rather than a public sector phenomenon.

So while the above factors have contributed to a limited extent to the growth of information occupations, they only account for a small part – about one-fifth – of the change in the size of the sector. The large majority of the information labor force – some 80% according to the data in fig. 2 – is concerned in a broad sense with the administration, coordination and organization of economic activity; typical instances of occupations within this category are managers, clerks, buyers, sellers, brokers, and accountants. They form the administrative or organizational superstructure which directs, coordinates, monitors and records activities taking place within the economy. To understand what it is that is causing the resource needs of this organizing or managing function to increase, we must consider the nature of technological progress, and in particular its tendency to cause an increase in the complexity of the economic system.

The economic process – the process by which goods and services are produced and distributed in an economy – is a complex system of interlinked and interdependent activities. These activities must be coordinated and organized. Numerous workers are typically involved in the provision of each of the goods and services used by the community. With the progress of technology the nature of each person's work has tended to change in two ways. It has tended to become on the one hand more *specialized* and on the other more *efficient*.

Specialization of individual tasks, or division of labor, means that each person in a chain of production makes a smaller contribution to the creation of each of the items emerging from the chain. The tendency towards increased specialization has been apparent through much of history. The transition from primitive communities to the early civilizations was marked by the emergence of specialist crafts and trades. The most dramatic step forward in this direction took place with the coming of the Industrial Revolution. Whereas previously the division of labor had left each craftsman or tradesman still largely responsible for the provision of a finished product or service, the division now became minute. Adam Smith's famous description of the production of pins illustrates the extent to which specialization was being practiced in some workshops as early as the mid-18th century; some eighteen individuals carried out different tasks in the chain of production. During the 19th and 20th centuries, the extent of the division of labor, and hence the number of different specialized tasks performed by workers in the industrialized world, has continued to increase.

Accompanying the increase in specialization has been an increase in efficiency. Greater efficiency can be defined, in our framework, as a reduction in the total quantity of labor time required for the output of a good or service – including the labor time embodied in capital equipment and tools used in the production process. The reduction of this required labor time, by means of inventing more roundabout techniques of production, has been the basis of technological progress. Introduction of more roundabout and indirect techniques results both in greater specialization and in increased efficiency. Productivity data confirm these efficiency trends: the quantity of real output produced by each production sector worker in the U.S. economy was 6.4 times greater in the year 1970 than in 1900.

If the effects of technical progress at the level of individual activities are an increase in efficiency and in specialization, the consequences for the economy as a whole are an increase in *output* and in *complexity*. A rise in aggregate output per worker follows by definition from an increase in labor efficiency in each unit. The complexity of an economic system is more difficult to measure than the gross output. There is an intuitively clear sense in which the introduction of more roundabout production methods, the spread of specialization and the increasing division of labor make the economy more complicated. A greater variety of inputs is required for each stage of production. The number of transactions among business units, and of internal transfers of intermediate goods and services within business units, grows. Thus the increases in complexity and efficiency bring about an increase in the informational tasks of managing and coordinating the economy.

If this interpretation of the nature of economic progress is correct, we should observe an increase in the size of the information sector as the productivity of industrial processes rises. Improvements in information handling efficiency should also feed back to the production sector, resulting in greater overall output. Both effects are in fact observed in industrial economics. We analyze them formally in the next section.

4. Modelling the information – productivity relationship

The quantitative analysis is based on a model of the interrelationship between the size of the information sector and the productivity performance of an economy. The mathematical details are given in the appendix. The theory is built up on the basis of a set of micro-analytic models of the effect of information inputs on the output or value of production and trading activities; it is then calibrated and applied for predictive purposes at the economy-wide level of aggregation. The micro models describe a variety of ways in which information inputs serve to increase either the efficiency of a production process or the value of an economic transaction. The models of production processes focus on the problems of monitoring and control. Typically they define a number of parameters which have to be observed and controlled in order for the process to function effectively. The parameters can be interpreted as a complete list of the items of information necessary to ensure effective management of the process in a given period of time (say a working day). The models of transactions, as opposed to processes, focus on the relationship between the usefulness of an input of goods or services and the extent of informational activity which accompanies the interaction between buyers and sellers. On the buyer's side this is the action of searching for the right product at the right price, and on the seller's side it is the action of informing the buyer of the nature and availability of the products offered.

Despite the variation in the informational functions under study – process monitoring, process control, market signalling, and market searching – we find that a similar mathematical form of the information–productivity relationship is derived in all cases. The form is given, in terms of aggregate variables, in eq. (A.20) of the appendix:

$$\frac{N_I}{N_P} = k \cdot \frac{I^T}{I_P} \cdot \left(\frac{\gamma_P}{\gamma_I}\right)^{1/2} .$$

This states essentially that the ratio of information to production sector workforce (N_I/N_P) will rise as the square root of the ratio of production sector to information sector productivity (γ_P/γ_I).[7]

[7] This holds if I_P/I^T, the proportion of total information sector resources used as inputs to the production sector, is constant. This condition is approximately satisfied for the periods under study

Fig. 3 illustrates the results of a test of this hypothesis, based on time-series data for the United States from 1900–1970. The graph compares the predicted growth of information handling requirements, as given by the above square root law, with the observed growth in the information sector workforce. For the purpose of this test it is assumed that information sector productivity is constant over the period under study: this assumption is relaxed in subsequent analyses. The model is calibrated [that is, the constant k in eq. (A.20) is set so that the information workforce size is correct] at the year 1900. The data on which the test is based are given in table A.1 of the appendix.

The solid line in fig. 3 shows the actual percentage of information labor in the workforce. The broken line indicates the ratio which would be predicted by the theory if the model were fitted at the year 1900 and then driven by the rate of growth of output per production worker in subsequent decades [see table A.1, line (7)]. The graph shows that the pattern of change predicted by the model, though not precisely correct, is broadly consistent with the actual historical trend. It demonstrates that the information workforce has grown in approximate proportion to the increased information requirements arising from changes in economic productivity.

Fig. 4 contains the results of a more complex application of the model, in which trends are forecast to the year 2000, and in which changes occur in the productivities of both the production and the information sectors. The figure contains two graphs. The first [fig. 4(a)] tracks the size of the information workforce as a proportion of total non-agricultural employment. The second [fig. 4(b)] shows three productivity trends: (A) Production worker productivity, (B) information worker productivity, (C) overall economic productivity.

The interdependence among the four curves is governed by two mathematical relationships: the equation linking information requirements and productivity, and the identity defining overall productivity growth as a weighted average of productivity growth rates in the two component sectors [expressions

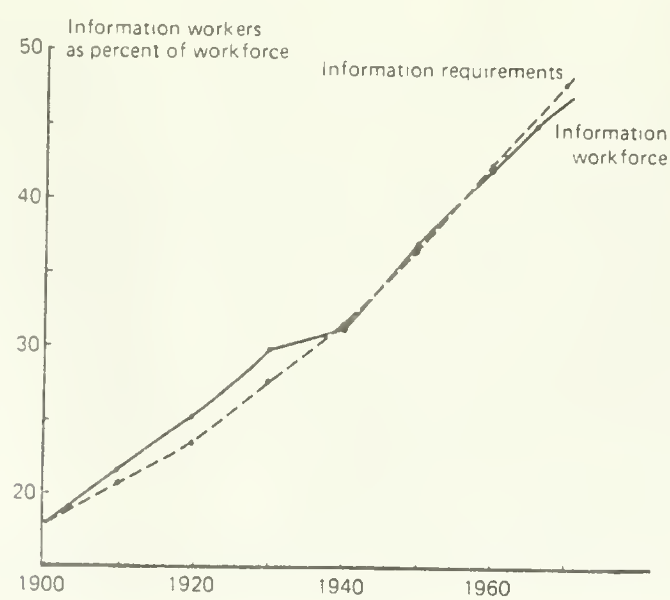

Fig. 3. Predicted growth of information processing requirements and actual growth of U.S. information labor force, 1900–1970. (Model calibrated at year 1900.)

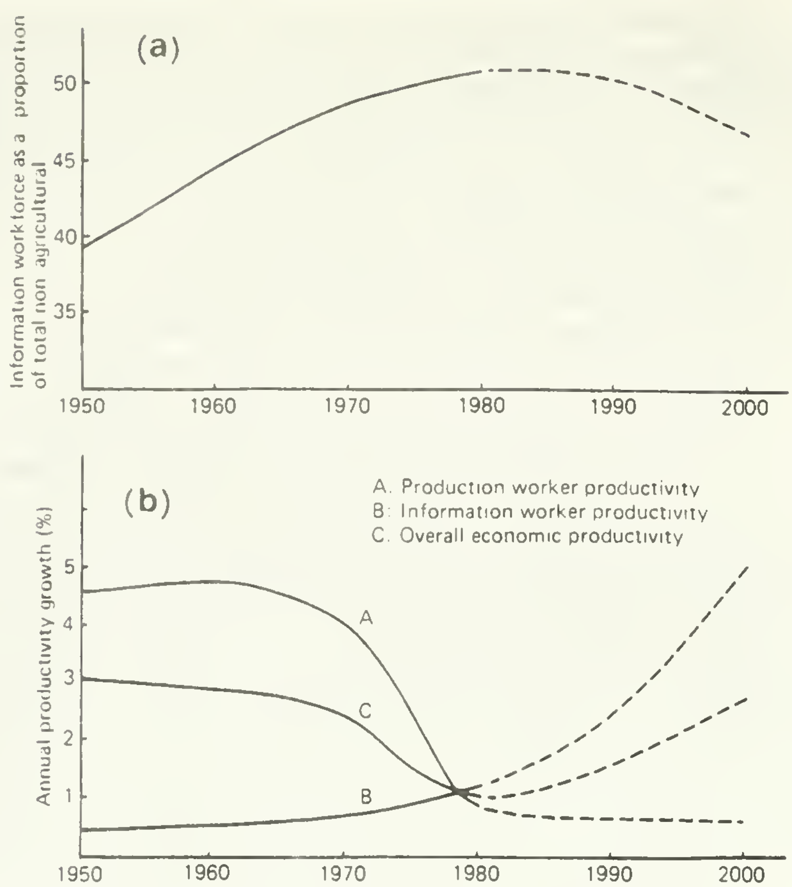

Fig. 4. Size and productivity of the information and production sectors, 1950–2000. (a) Information workforce size. (b) Productivity trends (five year moving average, to smooth out transient fluctuations). (*Sources*: See appendix, table A.2 and related text.)

(A.24) of the appendix]. Each graph covers the years 1950 to 2000. For the period from 1950 to 1980 the results are based on actual data, and are represented by solid lines; from 1980 to 2000 production and information sector productivity data are forecast, and are represented by broken lines. The method of derivation of the graphs is described in the appendix, and the data corresponding to each curve are contained in table A.2.[8]

The following pattern of productivity change and sectoral growth is apparent from fig. 4. In the period up to the mid 1960s, productivity was rising rapidly in the production sector, at over 4% per annum. Information sector productivity growth was very small by comparison – approximately 1/2% annually. The consequences were twofold: a rapid rise in the number of workers in the information sector, due to the mechanism described in the previous section [see fig. 4(a)]; and a gradual decline of overall productivity growth in the economy, since lower-productivity labor was accounting for an increasing proportion of the whole [see fig. 4(b), curve C].

During the 1970s the industrial productivity growth rate fell very steeply, to less than 1% per annum. At the same time information worker productivity was beginning to rise, due especially to the widespread use of computing

[8] Note that information sector productivity is not measured directly, but is obtained from the model as a solution of the simultaneous eqs. (A.24).

equipment to handle routine office functions. This improvement was not large enough or sufficiently timely to prevent overall productivity growth from showing a sharp fall during that decade, a fall which has been extensively documented and discussed [Denison (1979)]. However the closing gap between the two sectoral productivity growth rates between 1970 and 1980 [curves A and B on fig. 4(b)] was sufficient to cause a noticeable reduction in the rate of growth of the information workforce by comparison with the previous ten years [fig. 4(a)].[9]

The model predicts for the 1980s a reversal of the previous decade's slowdown in economic growth. Provided that productivity trends in each of the two sectors continue as shown [curves A and B, fig. 4(b)], information worker productivity will grow faster than that of production workers. This will result in a levelling off and then a decline in the proportion of information workers in the economy, the ratio reaching almost exactly 50% at the peak [fig. 4(a)]. By 1990 the percentage of information workers will have fallen to about 49%; by the end of the century it is forecast under this model to have dropped to under 46%.

The center curve in fig. 4(b) shows that overall economic productivity growth will not continue on its current downward trend but will pick up again in the 1980s in response to improvements in information sector efficiency. This recovery is forecast even under the very pessimistic view of industrial productivity growth implied by the path of curve A in the period 1980–2000, because information sector resources are now a sufficiently large part of the total that improvements in their efficiency can more than compensate for poor performance in production technology.

5. Implications: The role of information technology

On the basis of the foregoing analysis we can draw the following broad conclusions.

The 1980s will see a transition in which application of information technology will take over from advances in industrial efficiency as the principal source of economic growth. This transition is brought about by the two long-term trends noted at the beginning of the paper: the emergence of a large information sector and the development of new technologies for information processing. The first of these trends dates from the nineteenth century, and has now reached the point where about half of the resources of the economy are used for information handling tasks. The second is much more recent; automated technology was not introduced into office environments on a large scale until the last decade. Fig. 4 shows that the introduction of information technology has not come in time to prevent a sharp drop in overall economic performance during the 1970s. However, on present trends it should lead a strong recovery in the next decade and a half, with the rate of annual economic growth approaching the 3% level achieved between 1950 and 1970.

The major assumption on which the forecast portion of our analysis rests is the ability of information sector productivity to continue to rise at the rate

[9] We recall from the appendix, eq. (A.20), that the information workforce size is determined by the differential productivity growth rates of production and information labor.

implied by fig. 4(b), curve B. We conclude by discussing the realism of this assumption, and noting the private and public policies which might be required for the performance target to be realized.

With regard to continuing information sector productivity growth, we can point to several reasons why the present upward trend should continue:

(1) Continuing improvements in capabilities and cost-performance characteristics of information technology at basic component or device level

Most items of electronic information technology are based on four types of elementary components: memory devices, processing elements, transmission links and input/output devices. In all four cases costs per unit of functional performance have been falling rapidly over the last two decades and will continue to drop for the foreseeable future. Costs per unit performance at the component level are typically falling at between 15% and 35% annually for these items.[10] Among the technical developments which will ensure further cost reductions in the coming several years are:

(i) for memory devices, increases in the number of storage elements per semiconductor chip (currently 64K for state-of-the-art commercial products, but rising shortly to 256K and then to 1M), development of optical discs and high capacity rotating magnetic discs, and refinement of bubble memory technology,
(ii) for processing elements, increases in the scale of integration and reductions in production costs for semiconductor microprocessors,
(iii) for transmission links, improvements in optical fiber, microwave and satellite communication technology, and
(iv) for input/output devices, development of cheaper optical character readers and keyboards (data input) and lower cost printers and display units, especially solid state (data output).

(2) Improvements in capabilities and cost performance characteristics of information technology at the system or application level

While these technical developments at the component or device level will assure productivity gains in the medium and long term, near term improvements in white-collar efficiency will depend largely on new applications of existing components. The main areas of information system innovation will be computing, telecommunications, database access and office automation. Such systems can be used to substitute for labor and other capital inputs in industry and commerce, resulting in improved productivity: computing equipment reduces clerical staff needs, enhanced telecommunications services can improve utilization of managerial time, database access enables improved decision-making, and so forth. Improvements in performance per unit cost are not as dramatic at the system as at the component level, since much of the cost is accounted for by casing, power supply and other items less subject to price

[10] Many estimates of the rate of these cost reductions have been made. Among the more comprehensive compilations is Phister (1979).

reductions; nonetheless falls in real costs in the region of 10%–25% per year are typical for telecommunications and computing equipment.

(3) *Development of the telecommunications infrastructure*

Many of the productivity-enhancing office technologies now becoming available require the use of sophisticated national private or public telecommunications networks. Distributed computing systems and remote database access services are tending to replace stand-alone installations; similarly word processing and other office automation products are increasingly being interlinked through private or public communication links. Very large investments are currently being made throughout the industrialized world in terrestial telecommunications systems, satellite transmission facilities and cable television networks to carry voice, video, data and text traffic. Telecommunications infrastructure investments are currently accounting for about one tenth of Gross Fixed Capital Formation in the United States and Western Europe [Jonscher (1981)]. Microeconomic studies demonstrate that these will show high returns in coming decades as businesses make use of the communications facilities to improve the productivity of information handling processes.[11]

(4) *Gradual reduction of institutional and social barriers to the introduction of information technology*

Widespread acceptance of new technologies in the office is often hampered more by institutional and social barriers than by technological limitations. These impediments are being overcome as evidence builds up of the benefits available from office automation, and as more individuals become educated to use keyboards and programmable systems. Resistance to the introduction of new technology will not disappear; concerns over employment impacts and effects on working patterns will continue to be expressed, often justifiably. However, the direction of change broadly favors more rather than less acceptance of the innovations. Further improvements in information sector productivity at the aggregate level would be forthcoming for this reason alone, even without any increase in the range and performance of available technology.

It is these and related factors which lead us to believe that information labor productivity growth rates of the magnitude indicated in fig. 4(b) are attainable between now and the year 2000. It should be cautioned, though, that these improvements may not be realized without active intervention by governments and other policy makers. In particular, the cost-performance data quoted in paragraphs 1 and 2 should not be taken as evidence that information handling efficiency will rise inevitably; there are many steps between the availability of a higher performance chip and the achievement of more efficient information management in the economy as a whole. The governments of several countries

[11] A program of such microeconomic studies is being carried out by Communications Studies and Planning International Inc., New York, with particular emphasis on the contribution of telecommunications systems to productivity. Studies have been carried out to date in the United Kingdom, Kenya and the Philippines; these show benefit/cost ratios (ratios of productivity gains to the cost of providing telecommunications facilities) of at least 5:1, and in excess of 100:1 for some users.

have responded to this need by appointing commissions to examine policy options in the information and communications area. The Organization for Economic Cooperation and Development has also undertaken several analyses of this kind. Among the recommendations proposed by such studies are: accelerated investment in public telecommunications facilities, additional research and development funding for information technology industries, provision for greater computer literacy in educational programs, and implementation of schemes to alleviate job displacement effects of new technology.

In an environment of scarce capital resources an additional public and private policy concern is obtaining capital to fund investment in the technologies we have identified. Despite the large increase in spending per worker documented in fig. 1, investments in machinery to assist white-collar functions still lag massively behind investments in equipment for supporting blue-collar occupations. Our data suggest that, given the extent of information handling requirements in the economy as a whole and the degree of potential substitutability between information and other inputs to industry, this level of investment represents only the tip of an iceberg. Major progress has already been made in the automation of routine data handling functions and of lower level clerical activities. The major challenge and opportunity which remains is the achievement of productivity growth in the remaining – non-routine and higher level – white-collar functions.

Appendix: Mathematical framework

The theoretical framework on which the results quoted in this paper are based is described in this appendix. It establishes mathematical relationships among the sizes and productivities of the information and production sectors. The theory is developed on a very disaggregated level on the basis of simple models of the effect of information inputs on the output or efficiency of production or trading activity; it is calibrated and applied for predictive purposes at the economy-wide level of aggregation.

A.1. Technology of production and information handling

The economy is divided up in our model into two types of units, termed production units and information units. The former use production labor to produce products, the latter information labor to produce information services. The following terminology is used to define inputs and outputs of a production unit: n_p number of production workers in a unit, x^i_P, z^i_P quantity of input goods and information services, respectively, x^o_P quantity of output.

The following terms define inputs and outputs of an information unit: n_I number of information workers, x^i_I, z^i_I quantity of input goods and information services, respectively, z^o_I quantity of output.

The output per person of each type of unit is determined by two factors: the *efficiency* measure η and *productivity* parameters γ_P, γ_I:

$$x^o_P = \eta\gamma_P n_P, \qquad z^o_I = \eta\gamma_I n_I. \tag{A.1}$$

The quantity η is a function of the volume of information services (z^i_P or z^i_I) serving as input to the unit: its interpretation is discussed in the following section. The productivity factors are the basic technological parameters whose variation drives the model through time.

A.2. The information-efficiency function

The analytic core of the theory is a set of micro models in which information inputs serve to increase either the efficiency of a production process or the value of an economic transaction. In the terminology of the previous section, they link efficiency, η, with information input, z. Throughout this section z should be interpreted as the level of information services input per unit of output, i.e., for production and information units respectively:

$$z = z_P^i / x_P^o , \qquad z = z_I^i / z_I^o . \tag{A.2}$$

The models are designed to identify a functional relationship between efficiency and information input

$$\eta = h(z) , \tag{A.3}$$

which is applicable in a wide range of economic settings.

Four examples of models yielding such a function are given in Jonscher (1982a). The models are based on the behavior of an agent who is engaged in a single well-defined activity, such as controlling a process, monitoring a worker, searching for a price or promoting a product. Equilibrium levels of information resource use can be deduced by applying an optimization model [see eq. (A.14) below].

One is a process control model in which an event arises randomly (e.g., distributed in time as a Poisson variable) which has the effect of reducing output from its normal value Y^* to some lower value εY^*. The long-run average frequency of occurrence is μ. The measure of information processing, z, determines the mean frequency ν with which the process is monitored and corrective action taken, in accordance with the linear relationship $\nu = cz$, where c is a constant. The relevant measure of efficiency, η, is the actual average output as a proportion of the ideal average output Y^*. We can show that under appropriately defined conditions the efficiency is approximately given by

$$\eta = 1 - (1 - \varepsilon)\mu / 2cz . \tag{A.4}$$

Thus if we define $\beta = (1 - \varepsilon)\mu/2c$, we can write $h(z)$:

$$h(z) = 1 - \beta / z . \tag{A.5}$$

This model is valid in a wide variety of circumstances. No particular statistical distribution of either event occurrence or monitoring schedule need be specified, provided at least one is random.

Another example of such a micro-theory model is that of market signalling. A seller offers a product with some attribute q; the value to the buyer, V, is a function of the difference between the actual attribute q and the buyer's 'ideal' or desired attribute q^*:

$$V = V_0[1 - a(q - q^*)^2] . \tag{A.6}$$

where V_0 and a are constants. We wish to determine the expected value $E(V)$ of the transaction to the buyer as a function of the amount of information, z, which the seller provides on this attribute. The information takes the form of a signal which is distributed normally about q with a variance σ^2 given by

$$\sigma^2 = \sigma_0^2/z\,, \tag{A.7}$$

σ_0^2 is a constant. We can show that the expected value of the product to the buyer, $E(V)$, given a quantity z of information, is

$$E(V) = V_0[1 - 2a\sigma_0^2/z - a(q - q^*)^2]\,. \tag{A.8}$$

We interpret the efficiency of the transaction, η in expression (A.3), as the ratio of actual sale value $E(V)$ to the value V^* when the information regarding q is perfect (i.e., $z = \infty$). Then, providing $a(q - q^*) \ll 1$,

$$h(z) = \eta = E(V)/V^* \simeq 1 - \beta/z\,, \tag{A.9}$$

where β is the constant $2a\sigma_0^2$.

These and other models described in Jonscher (1980, 1982a) show that the relationship linking efficiency η and the measure of informational input or processing z frequently takes the form $\eta = 1 - \beta/z$, or a close approximation to it. In each case β is a constant which depends on the technical and informational characteristics of the activity under study.

We wish to determine the optimal level of information input z^* which an agent will select in order to minimize the sum of information and labor costs per unit of product output cost.

We introduce for convenience the following approximation to the function $\eta = 1 - \beta/z$:

$$\eta = \exp(-\beta/z)\,. \tag{A.10}$$

We note that the two are closely related; the former corresponds to the first two terms of the power series expansion of (A.10):

$$\exp(-\beta/z) = 1 - \beta/z + \frac{1}{2!}(\beta/z)^2 - \ldots\,. \tag{A.11}$$

However (A.10) yields a more tractable form for the level of optimal information input z^*.

If the unit price of information services is c_I and the wage is taken as numeraire (i.e., equal to unity), the agent's objective is to

$$\min_z\{c_I z + n_P\}\,. \tag{A.12}$$

Substituting from (A.1) and (A.10) this becomes

$$\min_z\{c_I z + (x_P^0/\gamma_P)\exp(\beta/z)\}\,. \tag{A.13}$$

The solution for the optimum value of z, z^*, is

$$z^* = (n_P\beta/c_I)^{1/2}. \tag{A.14}$$

A.3. Application to aggregate data

The above analysis refers to a single production or information unit. To apply the model to aggregate (economy-wide) data, we proceed as follows:

Let

N_P = number of production workers,
N_I = number of information workers,
P^T, I^T = sum of the outputs of all production and information units, respectively,
I_P = that part of total output of information units which is used as input to production units.

In a closed economy, we obtain the following relationships between these aggregate quantities and the inputs and outputs of individual units:

$$\begin{aligned} N_P &= n_P \cdot P^T/x_P^o, \\ N_I &= n_I \cdot I^T/z_I^o, \\ I_P &= z'_P \cdot N_P/n_P. \end{aligned} \tag{A.15}$$

From (A.1) and (A.15) we obtain:

$$N_I/N_P = (\gamma_P/\gamma_I) \cdot (I^T/I_P) \cdot (z'_P/x_P^o). \tag{A.16}$$

If agents select the optimal level of information input to each production unit, we know from (A.2) and (A.14) that the equilibrium value of z_P^o/x_P^o is given by

$$z'_P/x_P^o = z^* = (n_P\beta/c_I)^{1/2}. \tag{A.17}$$

Therefore at equilibrium:

$$N_I/N_P = (\gamma_P/\gamma_I) \cdot (I^T/I_P) \cdot (n_P\beta/c_I)^{1/2}. \tag{A.18}$$

We introduce the following approximation. As productivity levels in the production and information sectors change, the cost of information services falls in inverse proportion to information sector productivity, and the number of workers per production unit falls in inverse proportion to production sector productivity. Thus

$$n_P = k_1/\gamma_P, \qquad c_I = k_2/\gamma_I, \tag{A.19}$$

where k_1 and k_2 are constants. From (A.18) and (A.19) we obtain the following expression for the ratio of information to production worker numbers in the economy:

$$N_I/N_P = k \cdot (I^T/I_P) \cdot (\gamma_P/\gamma_I)^{1/2}. \tag{A.20}$$

where k is the constant $(k_2/k_1)^{1/2}$.

We define γ as a weighted average of the productivities of the two sectors:

$$\gamma = \frac{N_P \gamma_P + N_I \gamma_I}{N_P + N_I} . \tag{A.21}$$

The productivity of the economy, G, is conventionally defined as the gross output per unit labor input, without distinguishing the production and information sectors:

$$G = \frac{P^T + I^T}{N_P + N_I} . \tag{A.22}$$

This is closely related to γ; from (A.1), (A.14) and (A.21) we have

$$G = \frac{\eta N_P \gamma_P + \eta N_I \gamma_I}{N_P + N_I} = \eta\gamma . \tag{A.23}$$

We use expressions (A.20) and (A.21) for two purposes in this paper. The first is to test the validity of the model over a historical period, 1900–1970, on the assumption that information sector productivity has remained constant. The data relevant to this test are given in table A.1. The footnotes to the table indicate the derivation of each line of data. Note that the agricultural sector is measured separately, so that the model can be applied to the non-agricultural economy. Lines (4) and (7) of table A.1 are reproduced graphically in fig. 3.

The second application of the model covers the period 1950–2000, using actual data for 1950–1980 and forecast trends thereafter. The data used in this application are shown in table A.2, and selected items are reproduced in fig. 4. The table is filled out as follows.

For years 1950, 1960, 1970 and 1980, lines (1) and (4) are taken from data sources, and lines (2), (3), (5) and (6) are entered so as to comply with the model. Line (1) is based on a breakdown, following the definitional guidelines discussed in section 2, of occupational statistics; the sources are: 'Detailed Occupation of the Economically Active Population, 1900–1970', U.S. Department of Commerce, Bureau of the Census, *Historical Statistics*, Series D233-682; 1975 and *The National Industry-Occupation Employment Matrix, 1970, 1978 and Projected 1980*, Bureau of Labor Statistics, Bulletin 2086, 1981. Agricultural workers are excluded. Line (4) is based on several separate indices of labor productivity, including *Handbook of Labor Statistics*, Bureau of Labor Statistics, 1981, Table 103 (2 indices) and *Historical Statistics*, Bureau of the Census, Series W 1-11 and W 12-21 (3 indices). Composite (economy-wide) productivity data are very sensitive to the method of data collection and analysis, and there are large differences among indices. In order to smooth out temporary fluctuations, a five-year moving average is used. Line (6) indicates, for each 10-year interval, the average annual % change in the ratio $A/(1-A)$; this is denoted b. Lines (2) and (3) are then the solutions of the following simultaneous equations in g_P and g_I

$$g = Ag_I + (1-A)g_P , \qquad b = \tfrac{1}{2}(g_P - g_I) . \tag{A.24}$$

These expressions are the first time difference equivalents of (A.21) and (A.20) respectively; note that $A = N_I/(N_P + N_I)$, $b = N_I/N_P$, and that I^T/I_P is

Table A.1
Actual and predicted growth of U.S. information labor force, 1900–1970 (see also fig. 3).

	1900	1910	1920	1930	1940	1950	1960	1970
(1) Total workforce, N' (thousands)[a]	29,031	37,291	42,205	48,686	51,740	58,999	64,537	79,726
(2) Information workforce, N_I (thousands)[a]	5,196	8,121	10,771	14,595	16,373	22,029	27,621	38,665
(3) Agricultural workforce, N_A (thousands)[a]	10,888	11,533	11,390	10,322	8,954	6,858	4,086	2,345
(4) (N_I/N')	0.179	0.218	0.255	0.300	0.316	0.373	0.428	0.485
(5) Index of production sector productivity γ_P[b]	1.00	1.16	1.42	1.87	2.36	3.26	4.56	6.39
(6) $[N_I/N_P]_{predicted}$[c]	0.401	0.432	0.478	0.548	0.616	0.724	0.856	1.01
(7) $[N_I/N']_{predicted}$[d]	0.179	0.208	0.236	0.279	0.315	0.371	0.432	0.488

[a] N_I, N_P and N_A are the numbers of information, production and agricultural workers in the economy based on the author's classification of occupational categories to these sectors. $N' = N_I + N_P + N_A$. *Source*: 'Detailed Occupation of the Economically Active Population, 1900–1970', Bureau of the Census, *Historical Statistics*, Series D233–682.

[b] *Source*: NBER Series, *Historical Statistics*, Series 4.

[c] $[N_I/N_P]_{predicted} = (\gamma_P)^{1/2} \cdot [N_I/N_P]_{1900}$ [see eq. (A.20), with γ_I, k and I'/I_P constant]; $[N_I/N_P]_{1900} = [(N_I/N') \cdot N'/(N' - N_I - N_A)]_{1900}$.

[d] $[N_I/N']_{predicted} = (1 - N_A/N')/[1 + N_P/N_I]_{predicted}$.

Table A.2
Size and productivity trends in the U.S. information and production sectors, 1950–2000 (see also fig. 4).

	1950	1960	1970	1980[a]	1990[b]	2000[b]
(1) Ratio of information to total workforce, A [c]	0.397	0.445	0.487	0.505	0.495	0.457
(2) % annual growth in production sector productivity, g_P	4.6	4.7	4.0	1.0	0.7	0.6
(3) % annual growth in information sector productivity, g_I	0.5	0.6	0.8	1.3	2.3	5.1
(4) % annual growth in total labor productivity, g [d]	3.0	2.8	2.4	1.1	1.5	2.7
(5) Differential % annual productivity growth rate of production and information sectors, (10-year average), $g_P - g_I$	4.1	3.6	1.5	−0.9	−3.1	
(6) % annual growth in ratio of information to production workers (10-year average), b [e]	2.0	1.8	0.7	−0.4	−1.6	

[a]Some data items extrapolated from 1978 and 1979.
[b]Forecast.
[c]$A = N_I/(N_P + N_I)$. Agricultural workers excluded. *Source*: see text.
[d]*Source*: see text.
[e]% change annually in $A/(1 - A)$.

constant. Line (5) shows for convenience the average value of $(g_P - g_I)$ in each 10-year period.

For the years 1990 and 2000 the following procedure is used. Lines (2) and (3) are completed first (see section 5 for discussion of the trends in these two variables). Line (5) is computed directly: lines (6) and (1) are then obtained by application of expressions (A.24).

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