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ALFRED P. SLOAN SCHOOL OF MANAGEMENT

Dr. Charles Jonscher
Booz Allen & Hamilton
and
M.I.T.

MASSACHUSETTS
INSTITUTE OF TECHNOLOGY
50 MEMORIAL DRIVE
CAMBRIDGE, MASSACHUSETTS 02139

An Economic Study of the Information Technology Revolution

Dr. Charles Jonscher
Booz Allen & Hamilton
and
M.I.T.

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INTRODUCTION

The growing significance of information - its creation, processing and management - in today's economies is well documented. The sociologist Daniel Bell (1973) observed that the developed world is entering a post industrial phase, in which "what counts is not raw muscle power, or energy, but information". Economists have attempted to quantify this phenomenon.[1] Studies show that businesses in the United States now spend more on the office-based functions of information handling than on the physical production and processing of goods; this proportion was less than 18% in the year 1900.[2] This shift of economic resources from the traditional productive activities of industrial and agricultural workers to white-collar information handling functions constitutes one of the major changes of this century in the structure of industrialised economies.

A related change has been the adoption of information technology. This technology is bringing about a transformation in the way business is conducted. Computers prepare invoices, issue cheques, keep track of the movement of stocks, and store personnel and payroll records. Word processing and personal computers are changing the patterns of office work. We show later in this paper that United States businesses are spending as much on information technology as on the technology of industrial production. The spread of information technology is affecting the efficiency and competitiveness of business, the structure of the workforce, and the overall growth of economic output. This transformation in the way in which information is managed in the economy has profound economic and social implications. It constitutes a revolution, which may have economic consequences as large as those brought about by the industrial revolution (Drucker, 1968).

In this study we describe three phases of this information technology revolution:

Phase 1: 19th Century - c.1960

> The growth of information management. Throughout this century the task of information management - of creating, manipulating, and communicating information - has been growing gradually but steadily as a proportion of the total economic activity. By about 1960 the information or white collar workforce overtook the production or blue collar workforce as the principal labor expense of the business community.

Phase 2: c.1960 - c.1990

The introduction of information technology. Beginning in the early 1960s, automation of office and factory work through the introduction of information technology began on a significant scale. By about 1990 information systems will have overtaken conventional production machinery as the principal technology expense of the business community.

Phase 3: c.1990 +

Integration. As the automated office functions and automated physical production systems within firms become integrated and networked, there is a reversal in the trend to separate out the information management tasks from the remainder of the economy. Information systems link customers to suppliers and offices to factories. In the consequent reintegration of economic activity, information technology plays a more central role in the strategy of businesses and the performance of the economy.

It is a popular conception that the primary driving force behind this information revolution has been progress in microelectronic technology, and more particularly in the development of integrated circuits or "chips". On this view, the reason why computing power which used to fill a room and cost $1,000,000 now stands on a desk and costs $5000, or why pocket calculators which used to cost $1000 now cost $10, is that society happens to have benefitted from a series of spectacularly successful inventions in the field of electronics. As to why the introduction of information technology occurred when it did or took the path that it did - why data processing came before word processing, or why computers transformed the office environment before they transformed the factory environment - the popular conception is silent. And, since this technology-oriented view of the causes behind the information revolution offers little guidance as to the direction which technological developments have taken thus far, it offers little insight into the direction which they will take in the future.

This paper provides an economic analysis of the forces driving these developments. The initial part of the study is based on historical data. The sharp decline in price of information processing devices was not an historical accident. It happened in response toa set of economic and other forces, which caused the necessary development resources to be applied in this field. We first analyse those past developments and then assess how the same underlying economic forces are likely to shape future trends in the deployment of information technology.

ECONOMIC PRINCIPLES

Such an analysis must be based on a thorough understanding of the role of information in the economy. Economic theory has only recently addressed itself explicitly to the study of information as a distinctive type of commodity. In 1973 Kenneth Arrow, presenting the customary lecture of the winner of the Nobel Prize in economics to the Federation of Swedish Industries, chose to speak on the subject of "Information and Economic Behavior". He described information as "an economically interesting category of goods which have not hitherto been afforded much attention by economic theorists" (1973, p.8). The purpose of the address was to "indicate the importance of information as a variable affecting economic behaviour and the rather diverse ways in which the economic system is affected by its scarcity and diversity" (p. 25). The thoeretical literature now referred to under the heading of the "economics of information" is concerned with analysing the consequences of imperfect or costly information in areas of economic theory in which information had previously been assumed to be perfect or costless.[4] Attention was first given to information about prices, following a seminal paper by Stigler (1961), and has since been extended to cover a wide range of "attributes" about which economic agents are uncertain: product quality (Akerlof, 1970), insurance risk (Rothschild and Stiglitz, 1976) and labor quality (Spence, 1974). It has been pointed out that the phenomena of informational deficiency and diversity may have quite profound consequences for conventional economic theory (Arrow, 1973); a satisfactory general model of economic activity in which information needs and activities play a major part has yet to be developed.

The special characteristics of information as an economic commodity

The purpose of much of this literature is to assess how the economic attributes of information differ from those of other kinds of goods. An important attribute of information as an economic good which is given much attention is that it is not depletable. This gives rise to the well-known "public good" property of information: if a piece of data is of value to many agents, then (provided reproduction costs are low) it is in the public interest for it to be made available to all of them at a low price. However, unless rights to ownership are granted which allow a higher price to be charged, there is a loss of incentive to create knowledge. The consequences of such characteristics of knowledge as a commodity are extensively discussed in relation to the economics of research and development, copyright and patent regulations, and more generally in discussions of the economics of intellectual property. This is now textbook material[5].

There is however an additional characteristic of information which we will show to be of overwhelming importance in understanding the changes we are seeing in the way information is handled in the economy. This is the fact that economic information is embodied in symbols, and the value of the information is independent of the value of the symbols by which it is represented. Thus a market research study (a piece of economically valuable information), undertaken at a cost of $10,000, may be sent to its recipient in the form of a leather bound document costing $25 or in the form of a machine readable magnetic tape costing $5. The creation and distribution of the symbols representing the information will have certain economic characteristics (e.g. cost of production of the document or magnetic tape, cost of transmission, cost of storage) which I will refer to as "the economics of symbol manipulation." These characteristics will differ greatly from medium to medium, but will be independent of the value of the information which the symbols represent. Thus the cost of making a hundred copies of the market research report will differ greatly depending whether the chosen symbolic representation is typeface on paper or electronic encoding on tape, but will be largely unrelated to whether the cost of the market research was $10,000 or $5,000.

The production of market research information has its own peculiarities, which will exhibit the characteristics which we described as typical of intellectual property. We can use the term "economics of knowledge" to refer to these, to distinguish them from the economics of symbol manipulation; we use the term economics of information to cover, somewhat ambiguously, both cases.[6]

The two features of the economics of symbol manipulation which have driven forward the information technology revolution are first, that the variety of symbols by which economic information is represented is very small despite the huge variety which exists in the content of the information, and second, that the physical embodiment of symbols can be changed without affecting the value of the information they represent.

The first characteristic allows for enormous economies of scale in the production of machinery which manipulates information. A very large proportion of all economically valuable facts are created, stored and communicated using only 26 characters and 10 digits. Therefore once a typewriter or word processor which can handle these 26 characters and 10 digits is produced, an identical machine can be used equally for recording information about a farm, an automobile factory or a hamburger restaurant. This phenomonen has no counterpart in the economics of non-information manipulation. Machinery used in farming cannot be used to manufacture automobiles or cook hamburgers. Similar economies of scale exist in handling information represented other than in alphanumeric text. The human voice, a very important mode of communication of business information, can be accommodated (satisfactorily) within the bandwidth of a telephone line having the internationally accepted standard bandwidth of 300-3400 KHz. The telecommunications networks which have been constructed across the country and the world to handle such voice messages can equally accommodate conversation on any topic from the petroleum business to clothing manufacture. Again, there is no counterpart in the realm of non-information goods; different kinds of trucks are needed to transport petroleum and to transport clothing.

The second characteristic, the fact that the value of information is independent of the size, weight, or other physical attributes of the symbols by which it is represented, provides a second dimension for exploiting economies of scale in information handling. It means that the representation of knowledge in the form of symbols is not subject to resource constraints in the conventional sense of the term resource - material, energy, space. Provided the economics of the creation, storage, communication and finally interpretation of the symbols makes this worthwhile, the quantity of physical resources used to represent symbols can be reduced without affecting the value of the knowledge embodied. Once more, there is no analogous phenomenon in the realm of conventional (non-information) goods. An automobile manufactured to one hundredth of the usual scale does not have the same value to its user as a full size one, while market research information packed one hundred times more densely onto a magnetic tape retains the same value.

Electronics as the technology of information processing

We will describe in this paper how electronic technology has been used to exploit both of these characteristics of the economics of symbol manipulation - the economies of scale in manufacture afforded by the small number of varieties of symbolic representation, and the economies of resource use afforded by the independence of information value from the physical composition of the symbols in which it is represented.

Electronics is almost synonymous, in today's economies, with information technology. This is what distinguishes electronics from other forms of technology, such as steam, diesel, nuclear or electrical power machinery. In these latter systems the power levels present in the machinery are sufficiently high that useful physical work can be performed - work which prior to the industrial revolution would have been done manually. An electronic system is a particular case of an electrical system in which the power levels are so low that substantial physical objects cannot be manipulated - only symbols can. The power in an electronic circuit is sufficient to represent a character of information, but not to operate an elevator or turn a lathe. In so far as it replicates human effort, it performs functions requiring intellectual rather than manual labor.

A great deal could be written to clarify and perhaps qualify the statements in the above paragraph. There are a few cases (for instance in the medical field) of electrical systems in which power levels are sufficiently weak to classify as electronic but are nevertheless used to have a physical effect other than the manipulation of symbols. Conversely even an electronic - or symbol manipulating - system may develop enough power to move a physical object such as a printer key. So long as the physical objects being manipulated have no other function than to represent symbols (as in the case of printer keys), we regard the activity as one of information handling rather than physical labor. Strictly speaking, one should regard the printer on a computer system as an electrical rather than electronic component; it is thus an item of information technology which is not electronic. Perhaps more importantly, there still exist purely symbol manipulating sytems which have no electronic or even electrical components. They are mostly either mechanical, in which case they are usually being replaced by electronic systems (an example is the traditional semaphore-style railroad signal), or optical, in which case they are still in the pre-commercial phase (as in the case of optical computers). In both cases they are of relatively minor economic significance. For the purpose of this study we will ignore all these qualifications, focusing on electronics as the pre-eminent information processing technology of the present era.

Because of the interdependence between the cost of production and the volume of production of information technology components, an economic analysis of the information technology phenomenon must have both a demand and supply side. The demand side must assess what it is about the development of a modern industrialised economy which has caused the information management requirements of economic agents to grow. The supply side must consider the way in which costs of information technology components vary with the volumes demanded. We consider these two points respectively in the next two sections.

PHASE 1: THE GROWTH OF INFORMATION MANAGEMENT

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, organising, coordinating and developing the many individual productive activities. The information handling activities are those of management, administration, clerical work, accounting, brokerage, advertising, banking, education, research and other professional services. Their counterparts we term production activities: factory, construction, transportation, mining and agricultural work.

Identifying the pattern of expenditures on information activities is made possible by the very high degree of occupational specialisation present in modern societies. We can use occupational statistics to distinguish two kinds of labor in the economy:

1 information labor, comprising the activity of all individuals whose primary function is to create, process and handle information;

2 production labor, 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 classified as information labor. 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.

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 as information labor. Conversely, if a person is classified as a sheet metal worker his principal output is worked metal and not information; we therefore classify this as production labor. 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 activites 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; we address this issue later, in the discussion of Phase 3 of the information revolution. 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.

Table 1 shows the historical trend in the percentage of the United States workforce accounted for by information workers. In the year 1900, it was only 18%; it has risen steadily throughout the century, reaching 53% by 1980.

This growth in the information workforce constitutes what we describe as the first phase of the information revolution, namely the transition from an economy in which most resources were expended on the production task - undertaking productive activities - to one dominated by the information handling task - managing, coordinating and developing these productive activities.

What do information workers do? Figure 1 shows a breakdown of the functions they perform. The data are based on an allocation of occupations to functions in accordance with occupational definitions published by the Bureau of Labor Statistics. The categories have been chosen to allow us to distinguish among the major functional roles performed by the information sector. A further 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 constituents of the former category. The latter category 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 organise economic production. The relative sizes of the two groups are shown on the right hand side of figure 1. It is clear that the great majority of information workers, some 80%, fall into the latter group, being concerned with current information management and coordination rather than contributing to the capital stock of knowledge.

Figure 2 provides a diagrammatic representation of the functions performed by that four-fifths of the information workforce engaged in the management, coordination or organisation of economic activity. The figure illustrates a chain of production involving two firms; each firm takes as its inputs raw materials from another firm, and provides outputs to the next firm in the chain. Clearly this representation is simplified; in reality each firm will have several major sources of input and usually more than one destination of output. Accompanying the production activity in each firm is an information management function. Both these labels, production and information management, should be interpreted very broadly. The production function includes all those activities which are part of the chain of material processing and handling leading to the supply of goods and services by the firm. The information management function includes, as we have said, all activities which are concerned with organising, coordinating, controlling, monitoring, or recording the production activity.

The functions of management - or organisation, coordinating and monitoring - are by their nature information handling functions. It is information - symbols, words, messages - which flows along the channels of communication and control in an organisation. The occupations we have listed in the management sector (administrators, clerks, accountants, and the like) are primarily office-based and make use of products and services designed for handling information: paper, pens, files, telephones, computers.

It is because some 80% of all information processing activity in the economy falls into the categories represented on figure 2 (as opposed to such functions as education, research and development) that an appreciation of the nature of these information handling requirements is fundamental to an analysis of the demand for information technology. To understand why it is that the resource needs of these organising or managing functions are increasing, 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 growing complexity of economies

With the progress of technology the nature of productive work has changed in two ways. It has tended to become on the one hand more **specialised** and on the other more **efficient**. Specialisation 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 specialisation has been apparent through much of history. The transition from primitive communities to the early civilisations 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 specialisation 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 specialised tasks performed by workers in the industrialised world, has continued to increase. The chains and networks of production have become so complex that a typical worker now makes only a tiny contribution to each of the final products with which he or she is involved.

Accompanying the increase in specialisation has been an increase in efficiency. Greater efficiency can be defined 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 specialisation and in increased efficiency. Productivity data confirm these efficiency trends; the quantity of real output produced by each production sector worker in the US 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 specialisation, 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 average labor efficiency in business units. The complexity of the economic system is more difficult to measure than the output. There is an intuitively clear sense in which the introduction of more roundabout production methods, the spread of specialisation and the increasing division of labor make the economy more complex. 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. As industrial technology develops, the processes of production leading to the final output of goods and services becomes more complex. The organisational 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 benefitted from comparable efficiency improvements, the number of information workers must grow in response to this increasing organisational task.

If this interpretation of the nature of economic progress is correct, we should observe an increase in the size of the information workforce as the productivity of industrial processes rises. This effect is in fact observed in industrial economies.

The author has produced a mathematical model of the interaction between productivity growth and the growth in information requirements arising from the need to coordinate or organise production. This model shows that information handling requirements can be expected to rise with increasing productivity, but not in direct proportion to such increases. The forecast growth of information requirements is in fact equal to the square root of the growth rates in productivity - the square root law corresponding to a point mid-way between the extreme cases of (1) information requirements rising in direct proportion to productivity increase and (2) information requirements not responding to productivity increases at all.

Figure 3 illustrates the results of this modelling exercise, based on data for the United States from 1900 to 1970. The graph compares the growth of information handling requirements, as given by the above square root law, with the observed growth in the information workforce. The shaded line shows the actual percentage of information labor in the workforce, while the solid line provides a measure of the growth of information requirements consequent on the productivity increases which have taken place during that period. The figure shows that the pattern of growth in the information workforce, though not corresponding precisely to that implied by increasing specialisation and complexity in the economy, is broadly consistent with those factors. It demonstrates that the information workforce has grown in approximate proportion to increased information requirements arising from changes in economic productivity.

PHASE 2: THE INTRODUCTION OF INFORMATION TECHNOLOGY

As the proportion of the costs of businesses accounted for by information handling rose, so did the incentive to introduce technologies which could automate information processing tasks. Technological developments in the production sector were having 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 databases, word processors and a wide range of other data handling equipment.

Electronics was, as we stated earlier, the key technology adopted to achieve this automation of information processing tasks. We do not provide here a history of the early years of development of information processing machines; this is well documented (Beniger, 1986). Among many key milestones were the invention of the transistor in 1948 and the integrated circuit in 1959. We are concerned here with understanding not the exact timing of the initial inventions but the subsequent path of cost reduction and demand growth.

The production of electronic components is subject, like other production processes, to the experience curve effect. This is the empirically well established fact that the unit cost of production of industrial goods tends to fall by an approximately constant factor with each doubling of the cumulative output (i.e. the output from the date when production began) of the item in question. This effect has been estimated for numerous industries, especially by the Boston Consulting Group (1968). The constant factor by which the cost of output falls with each doubling of output lies in the range 20-30% for a wide variety of products, including those in the aerospace, automotive, chemical and textile industries.

An excellent description of the way in which this phenonomon has affected the costs of silicon chip production is given in Noyce (1977). This shows that for a period of approximately two decades the cumulative output of integrated circuit devices increased by a factor of two in every year.[7] This remarkable growth in output - corresponding to a total increase of one thousandfold in a decade and a millionfold in the two decades studied - showed a surprising consistency; it did not slow down appreciably in the years following this analysis. Over the same period there was a similarly steady fall in the cost per unit of performance delivered (specifically, binary memory). This drop in cost amounted to approximately 35% per year (compound, corrected for inflation).

Figure 4 shows that this 35% fall in annual cost can be broken down into components. On the one hand technological progress has allowed the number of bits stored on each silicon device to be increased, from only one in the year 1967 to 1K (1024) in 1971 and now to 1 million or more.[8] The other source of cost decline is the conventional experience curve effect acting on the cost of production of each generation of silicon device taken separately - representing progress in the methods of manufacture.

We stated in the introduction to this paper that we would show how the cost behaviour of electronic circuitry is attributable to specific features of information as an economic commodity rather than to the specific attributes of electronics as a technology. We consider the two contributions to cost reduction in turn, starting with the experience curve effect.

This effect dominates over the importance of changing device capacity as a determinant of cost. The experience curve effect in semiconductor device manufacture accounts for about a 25% drop in cost per doubling of output.[9] This pattern can be confirmed by examination of the slopes of the individual curves on figure 4.

The contribution to cost decline of 25% per doubling of output accounted for by the experience curve effect lies clearly within the range of 20-30% which categorises most other industrial production activities. That the cost of electronic devices has fallen at the unprecedented rate of over 30% per annum is primarily due not to an intrinsically greater potential for cost decline but to the very large growth in demand. The doubling of cumulative requirements each year for a period of more than two decades is unmatched in other sectors, and it is this which has driven down costs at the rates we have noted. Expressed as an annual rate of decline, the cost curves in figure 4 are much steeper than those for other industrial products. However, expressed as a fall in cost per unit of output growth, they are not appreciably different.

What, then, has caused the unprecedented growth in demand? The clue to the answer lies in our earlier analysis of the changing information handling requirements of the economy during the period of build-up of the white-collar workforce. This revealed the existence of a now very large sector of economic activity - namely the sector of information processing - which is much more homogenous in character than the remainder of the economy. We noted in the earlier discussion of economic principles that information, viewed as a commodity, had certain peculiarities which made its handling unusually standardised in character. This is borne out by empirical data on information resource expenditure, which show a remarkably high degree of statistical regularity across firms, industries and economies. After working extensively with data of this kind one cannot help noticing how standardised are the informational activities carried out in diverse businesses. The number of billing clerks per accountant, of secretaries per administrator, of telephones per office worker - indeed practically any measure of the pattern of expenditure on information activities - appears to be very stable across industries. Office activities are information handling activities, and there is a very restricted number of ways in which information can be handled. There are a few different ways in which it can be stored (for instance on paper, on magnetic tape, on microfilm, or in the human memory), a few different ways by which it can be transmitted (in writing, in spoken words, in computer code) and a few different ways in which it can be processed (by hand, by electronic machines); that is about all. By contrast there are countless thousands of entirely different processes carried out on non-information goods. There is practically nothing in common between the actions of assembling furniture and mining coal; yet the office layout in the headquarters of a furniture manufacturer may be much the same as that in the headquarters of a mining corporation.

We can think therefore of an economy as containing, at the end of Phase 1 of the three phases of development which we study in this paper, a pool of applications ripe for automation. These applications - such as file handling, word processing, transaction support - are relatively uniform across firms and industries, so that they offer scope for automation in huge volumes. The path of cost decline and volume growth exhibited by information processing components in Phase 2 is consequent on the extent of this scope for automation.

We now turn to the second influence on cost reduction in micro-electronics - the increasing density of packing of logic elements onto individual devices. The fact that ever larger numbers of memory cells can be accommodated on a silicon chip is a consequence of a unique characteristic of the economics of symbol manipulation noted earlier, namely that the physical embodiment of symbols can be reduced without affecting the value of the information they represented. Any technology developed for representing symbols - be it electronics or otherwise - can exploit this feature.

It is interesting to consider whether a technology other than electronics could, if it had been adopted as an alternative basis for mechanising information processing, have exploited this feature as successfully. I speculate that it could. Two alternatives to electronics (electrons in wires) which have been developed as bases for symbol manipulation are optical (light in fibers) and fluidic (gas or liquid in pipes).[10] Clearly miniaturisation of either of these on the scale achieved in integrated electronics would require the development of very intricate mechanical production machinery. But so did and does the fabrication of microelectronic circuits. We must not underestimate the development efforts which have gone into the latter, nor hence the results which could be achieved if similar development funds and subsequent production scale were available for alternative technologies.

Why do we stress the extent to which trends in the economics of information processing can be explained through analysis of the economics of demand (by application of the principles outlined earlier in this paper) rather than by accepting that there are unique features of the technology of supply. The purpose is not to detract from the inventions which have been made in the electronics field, but to show by demystifying the role of exogenous technological inventions that relatively predictable economic forces are at play. We show now how these forces help to explain the differential rates of cost decline experienced by different device categories.

We can distinguish four separate functions performed by an information technology system:

A processing - numerical calculations, logical operations, sorting and related functions, almost all carried out in modern information technology systems by integrated circuits;

B memory - storage of text, data, image or other information, usually either in integrated circuit memory or on rotating magnetic devices (disk or tape);

C transmission - communication of information between remote locations, using either a private telecommunications network or the services of telecommunications network operators;

D input/output - the interface between the information technology system and the persons (or possibly machines) using it; the most common input device is a keyboard, the most common output a printer or the VDU screen.

Commercial information processing facilities such as computers, word processors and office automation systems typically contain sub-systems performing each of these functions. It is instructive to consider how the cost per unit performance of each of these functions has varied during the last two to three decades.

Figure 5 summarises the results of such an analysis. It must be stressed that the data on this figure (and in the text which now follows) is intended to be much more approximate than that presented earlier in this paper. When referring to the typical rate of cost decline of, say, memory devices, we must bear in mind that there are numerous different memory technologies in use, each subject to different cost pressures. The same is true for each of the other functional categories under consideration. Nevertheless I believe that the following broad generalisation can usefully be made.

(a) Processing

Since the late 1950s most processing in commercial computers has been effected by semiconductor logic devices. It has been subject to cost decline partly because processing speed has increased and partly because the number of logic elements on each device has grown. Many analyses have been undertaken of the rate of improvement in performance per unit cost of processing components.[11] A commonly-used measure which captures both these trends is million instructions per second per dollar (MIPs/$). Estimates of the (compound) annual rate of cost decline for the period of interest in our analysis (1950 - 1980) range from as high as 50% (Rudenberg) to as low as 27%[12], depending on the particular commercial products used as the basis of the estimation procedure. Based on the sources we have reviewed we conclude that a figure in the range of 30-40% per annum would provide a reasonable average of the trends which have been documented in this literature.

(b) **Storage**

Storage devices are, as we have noted, of two main types: semiconductor memory and magnetic memory. Semiconductor memory is embodied in integrated circuits, the cost decline characteristics of which are described in detail earlier (about 35% per year). Reduction in the cost per unit performance of magnetic tape and disk devices has been slightly less sharp. Data on costs of various types of storage device are provided by Phister (for the period 1960-1970), McKinsey and Company (1976-1986), Frost and Sullivan (1965-1985) and others.[13] The corresponding compound annual rates of cost decline, when adjusted to reflect constant value dollars, are 34%, 30% and 28% respectively. Adjusting some of the figures reported downward slightly to reflect over-optimistic estimates typically arising when a short time period is analysed, we have concluded that the range 25% - 30% is representative of the real rate of average cost decline reported in this category of components.

(c) **Transmission**

Arriving at a representative figure for rates of cost decline in transmission systems presents even greater difficulties, due to the wide range of communications media used. The underlying technology consists of a physical transmission medium (usually copper cable, fibre optic cable or electromagnetic radiation), coupled with electronic devices for coding and multiplexing (interleaving) signals at each end of the link. Copper cable, still the most common transmission medium, is a relatively mature technology not exhibiting significant cost variations except with the underlying price of the metal commodity. The electronics of multiplexing, routing and coding are subject to the same downward cost trends as the other electronic devices we have considered. Reflecting these various changes, it has been possible for telecommunications services operators to offer data transmission services at prices which have declined at approximately 15-20% per annum compound during the past two decades[14]. We can take this figure as representative also of the costs which private telecommunications network operators face when providing similar services internally to users within a corporation.

(d) **Input-Output**

The largest cost components within the category of input/output devices are printers, keyboards and VDUs. Printers contain a combination of electro-mechanical and electronic devices. During the past two decades printers have experienced a rate of cost decline estimated at approximately 10% per annum (A.C.T., 1977). Keyboards, visual display units and other input/output devices have also been falling moderately in cost during this period. The range 5-15% is a reasonable estimate for the rates of cost decline reported in this category of devices[15].

At the expense of repetition, we restress that these cost trends, illustrated in figure 5, are only intended to provide very rough guides as to the average cost behaviour of the many different components which fall into each of the four functional categories. For our purposes the absolute magnitudes of cost decline in each of the four cases (which is clearly subject to a relatively wide margin of error) are less important than the rank ordering of the four. On the subject of rank ordering there would probably be little controversy. While there would be dispute among specialists as to whether transmission costs have been falling at, say, 15% or 20% per year on average, there is little disagreement they have been falling more slowly than either processing or memory costs. Similarly it would be generally agreed that input/output devices display the slowest downward cost trend of all these functional categories.

We now consider the implications of these differential cost trends for the spread of different kinds of information technology applications in the economy. We have noted before that there is a large body of relatively homogeneous information handling activities taking place within the economy (relative, that is, to the heterogeneity of non-information handling activities). These activities are potential candidates for early automation through technology.

The lower part of figure 5 describes four stages through which business applications of information systems have passed during the time since their first introduction in the 1950s. We can associate each stage with one of the four decades between 1950 and 1990:

1 Stage 1: the 1950s. During the 1950s computers were designed essentially for scientific and mathematical, rather than commercial, applications. They were used almost exclusively in support of research, helping to perform calculations which would have been cumbersome or impracticable to solve manually. The emphasis in these computers was on their processing capability, rather than on the memory, communications and other functionality which has subsequently become important. FORTRAN, a language optimised for calculations rather than file management or communications ("FORmula TRANslation"), became the most popular programming language.

2 Stage 2: the 1960s. The 1960s saw the introduction of computers for the purpose of automating routine information handling functions in business organisations. They began to be used to hold payroll records, to assist in processing of accounts payable and receivable, and in support of stock control. We can describe this new main application of computers by the generic term file handling. The bulk of computer processing time was being used to store, re-order, and retrieve files containing large numbers of identically structured records; the amount of processing or calculation associated with the contents of each record was generally minimal. COBOL, essentially a computer language optimised for file handling rather than calculations, became the dominant commercial programming language.

3 Stage 3: the 1970s. The 1970s were the years in which remote terminal working, networking and communications became a feature of business computing. In the 1960s and before, a business computer installation was both physically and electronically isolated from its surrounding environment, typically in a "clean room" to which only operators (not even programmers) had access. Input and output to the machine was effected by physical carriage of paper tapes, punch cards, magnetic tapes, disks and computer printout into and out of this room. In the early 1970s this pattern changed radically; the central computer facility became connected to numerous terminals placed throughout the business organisation. Public and private data networks arose in the United States and other industrialised countries, and the electronic isolation of the mainframe computer in its clean room became a thing of the past.

4 Stage 4: the 1980s. The major new feature of computer use by businesses in the 1980s has clearly been the personal computer. Personal computing, or the placing of processing power at the desk of each individual requiring computing services rather than in a central facility, is such a characteristic feature of information technology in the past decade that the popular visual representation of a computer is no longer a large processing unit flanked by tape drives but rather a small screen and keyboard on a desk.

(To what extent is there empirical evidence to support this four stage characterisation of the development of information processing functionality and the approximate association of a new stage with each decade? A useful study seeking to test this hypothesis, following a lecture presentation of figure 5 by this author, has been made by Michael Epstein (1985).

He undertook a content analysis of issues of Computing magazine during the four decades under study, taking the incidence of advertisements and feature stories as the measure of the major new application area emerging in this industry. He confirmed that each of the four major functional areas I listed did indeed show a tendency to dominate their respective decades. I am grateful to Michael Epstein for this piece of research.)

Associated with each of these major new application areas is a principal new cost component in the information technology environment. These new cost components are also noted on figure 5.

1 Scientific and mathematical applications (Stage 1) are processing intensive; they require the computer to be designed primarily with a view to the effective execution of calculations and related logical operations. The earliest computers were essentially calculating devices.

2 File handling operations (Stage 2) are storage intensive. A computer used primarily for file handling must, by definition, be equipped with extensive peripheral memory devices to store the files. In the 1960s purchase of bulk storage devices - tape drives, disk drives and core memory - loomed large in commercial computer installation budgets.

3 Remote working or networking applications (Stage 3) are communications-intensive. The major new cost component was communications support - the provision of networks, communications processors, and other hardware and software to facilitate remote working and interconnection.

4 With the advent of personal computing (Stage 4) the input/output devices - keyboards, screens and printers - began to be a dominant cost of the machines. Previously, terminals had been incidental to the main cost center, namely the computer to which the terminal was attached. Now the terminal **became** the computer, the necessary processing capability being added at relatively low cost.

It is interesting to observe the consistency between the major new functional areas characterising these four stages of development, as shown in the lower half of figure 5, and the four patterns of cost decline shown in the upper half. This pattern is consistent with the notion that there is in the economy a vast pool - perhaps ocean is the more appropriate analogy - of relatively homogeneous information handling activities. These activites are potential candidates for automation through technology. With the progress of technology the relative costs of automated versus manual execution pass a breakeven level at which automation is worthwhile, whereupon the very rapid "virtuous circle" of growing demand and falling prices begins. We can expect the most rapidly falling cost component - namely processing - to reach this breakeven level first, followed by storage, followed by communication, followed by input-output intensive functions. Figure 5 provides a diagramatic interpretation of this process. The horizontal broken line represents the breakeven level, and the falling cost curves cut across it at intervals of, very roughly, one decade. I must emphasise that this feature of the diagram is intended to be purely illustrative; there is no suggestion of quantitative precision here.

We might ask why the lines in figure 5 have the different relative slopes we have noted. Once the threshold of cost had been reached where automation of the corresponding function was worthwhile, why did input/output costs fall at a rate much lower than processing costs, and the other two functions at rates intermediate between these two extremes? Following the general theme of this study, we would prefer not to have to resort to the explanation that the cost of production of input/output devices such as keyboards and monitor screens is **intrinsically** more susceptible to cost declines than semiconductor logic or memory. When measured as the percentage drop in cost for each doubling of cumulative industry output, a cost decline factor in the usual range of 20-30% per doubling of output is to be expected in the case of input/output devices too.

What makes the cost decline of keyboards or monitor screens so much less steep - say in the region of 10% per annum - is that neither are devices new to this phase of the information technology revolution. There was an enormous base of production experience, dating from the age of typewriters and televisions. Therefore the number of years required to achieve each doubling of cumulative industry output is much larger. The keyboards used in information systems (for terminals and personal computers) are based on electric typewriter keyboards, over 100 million of which had been produced before the advent of personal computing. The screens used in personal computers are based on cathode ray tubes in television sets, of which, again, hundreds of millions had been produced prior to their requirement in data processing systems. The technology of semiconductor processors is, by contrast, completely new. An increase of any given magnitude in the cumulative production output required to service data processing requirements corresponds to an increase by the same factor in cumulative world industry output of this technology.

Storage devices and transmission systems present intermediate cases. We have noted that storage devices can be divided into two main categories. Solid state memory (previously "magnetic core" and now semiconductor) is used for immediate access. This is technology which computing applications brought new to the world, and hence, consistently with our expectations based on the experience curve concept, is subject to very steep cost declines of the order of 35% per annum. Rotating magnetic memory (magnetic tape and disks) are - at least in the case of tapes - based on technology which has widespread application prior to and outside of the data processing environment (specifically, consumer and professional audio tape machines). Correspondingly, its introduction into information technology systems has had less impact on the rate of cumulative industry output growth and the annual cost declines observed are much lower. Magnetic tape memory is however only one of the major storage technologies in use; the others - disk and solid state - were newly developed for data processing applications. Therefore storage costs, when aggregated or averaged, fall at a rate closer to that of processing than of input/output devices (see figure 5).

Communications costs constitute another intermediate case, this time closer in cost decline to that of input/output devices. Communications costs in a data processing environment are made up in large part of the costs of renting or owning communication networks. Telecommunication networks predate data processing applications by some decades, having been built up for the purpose of voice communication. Voice communications networks were - as we will note later - the communications infrastructure appropriate to Phase 1 of the information revolution. They were already in existence to provide a backbone, albeit not a fully satisfactory one, for network applications in information systems when the need subsequently arose during Phase 2; subsequent cost declines have therefore not been as marked as they would otherwise have been.[16]

We have not attempted in the above discussion to analyse quantitatively the relationship between increasing demand and falling costs of devices of the different functional catagories noted on figure 5, as we did in the earlier analysis of integrated circuit manufacturing. A great deal more could be done to make this discussion more precise. All we have done at this stage is to indicate that the divergent cost trends exhibited by different functions within the overall information system environment are roughly consistent with a demand-driven explanation rather than one which falls back on the idea that there are differences in intrinsic susceptibility to cost reductions.

In summary, the pattern of cost decline in information technology devices during Phase 2 can be attributed to a combination of demand growth and price reductions: increases in demand lead to falls in price due to the experience curve effect, and the fall in price then leads to further increases in demand due to the usual downward sloping demand curve. This "volume-price loop" in the economics of technology is illustrated schematically in figure 6.

The arrow on the right shows the linkage from demand growth to price reduction, and the graph adjacent to that arrow illustrates the experience curve which gives rise to that linkage. The slope of a typical experience curve for information technology devices is shown on that graph.

The arrow on the left represents the linkage from price reductions to demand increases, and the graph adjacent to that arrow illustrates the downward sloping demand curve which gives rise to that linkage. The slope of the curve marked on that graph corresponds to the data on overall demand for semiconductor devices quoted earlier: price falls of 35% per annum have been associated, for a period of some two decades, with quantity increases of 100% per annum, yielding a (logarithmic) downward slope or demand elasticity in the region of 0.6 to 0.7.

In this section of the paper we have illustrated how this volume-price loop has characterised the trends in cost and demand for information technology devices during Phase 2. In fact the same phenomenon can be shown to have affected technological developments prior to the emergence of information technology (i.e. during Phase 1) - and will almost certainly influence the path of technical progress in the phase to come. We conclude this study by applying the lessons learnt from Phases 1 and 2 to predict some of the trends which are likely to emerge in Phase 3.

THE TRANSITION TO PHASE 3

There is a widely felt sense that the adoption of information technology in advanced societies, while already into its third or fourth decade, is only now beginning to have genuinely revolutionary consequences. This perception is shared by writers from various disciplines (Piore and Sabel, 1984, Strassman, 1985, Toffler, 1980) and by the policy makers in many industrialised countries.[3] In the 1960s and 1970s computers and related devices were largely applied to the streamlining of operations within individual businesses. They had relatively little effect on the nature of production within firms or on the nature of competition among firms. In the 1980s this has begun to change. Information systems are moving into areas beyond the individual business office. Telecommunications networks are linking offices to factories and customers to suppliers. Industries which are particularly dependent on information flows, such as banking and finance, already rely on information technology for many aspects of their operation. Other industries, such as manufacturing, are beginning to undergo similar changes as computer technology enters the factory. The retail sector is becoming increasingly automated as checkout desks become linked into computerised stock control systems.

This latest set of changes represents a transition to a new phase, which we call Phase 3. It is more difficult to define and measure than the previous two phases. Before describing it, we review the forces which led to the development of the previous two phases, and show how in an advanced industrial economy such as that of the United States, the preconditions for a new stage in this process for development are now in place. The timing of the three phases is illustrated in figure 7, which may be used as reference throughout this section of the paper.

Phase 1 was the era of development of production technologies, coupled with a build-up of information management requirements in the economy. This resulted in the employment of increasing numbers of information workers, as shown in figure 7.

While we have defined this phase by the increasing reliance on information workers, the main technological developments in this era were in the field of production technology, not information technology. This was to be expected. Since labor costs account for the overwhelming majority of all costs in the economy (salaries and wages make up some 75% of gross natural product), the rising curve in figure 7 provides a good estimate of the relative magnitude of resources spent on the two aspects of the economic problem we identified earlier: the production task and the information handling task. The Industrial Revolution came at a time when the production task was a major one, and production efficiency the chief determinant of economic progress. Consequently the energies of inventors and the resources of industrialists were directed towards improving the throughput of production activities. New machines in factories processed and produced goods more efficiently, and rail and road infrastructures were developed to transport and deliver the goods more quickly and cheaply. Effective management, organisation and the handling of information were relatively less urgent problems.

Thus, Phase 1 saw the emergence of the "volume-price" loop illustrated in figure 6: a series of virtuous circles of falling technology costs and rising technology demand. In Europe and the United States this process began in the late eighteenth and early nineteenth century, with the development of mass markets and the creation of the institutions of capitalism - especially the joint stock corporation, which made practical the raising of the finance necessary for large scale production.

The virtuous circle operates as follows. In response to economic incentives created by conditions of demand, resources are devoted to the development of technologies which reduce the cost of some productive activity. The products of those industries which were subject to technological innovation - initially the textile industry, then countless others, fall in price. This stimulates demands for the products, and hence for the machinery to produce it. Increases in the volume of production of the technology leads to decreasing technology costs, due to the experience curve effect. Falling technology costs lead to cheaper products, hence greater demand - so cycle begins again.

As we note in figure 6, this volume-price loop is driven by two analytic relationships: the downward sloping demand curve, which links falling prices and increasing demand, and the negative slope of the experience curve, which links increasing supply quantity and falling price. Both of these have been well documented in many product markets. Although we do not provide any quantitive analysis of either of these phenomena as they affected production technologies during phase 1, we have noted that their overall effect was to cause an increase by a factor of more than 6 in the labor productivity of the production sector in the United States during the course of this century.

The discussion of Phase 1 earlier in this paper described how this increase in production sector productivity gave rise to the necessary pre-conditions for the transition to phase 2. Figure 7 illustrates that by about 1960 the information handling burden in the United States had grown to the point where it was consuming about half of all economic resources. The curve beginning at the left end of the diagram indicates how the relative proportions of labor costs spent on information handling versus production activities had changed during Phase 1. The position of this line can be derived from the data in table 1 on the number of workers in the information and production categories, subject to an adjustment to reflect the higher average pay of information workers.[19] By 1960 the percentage of the workforce represented by information labor amounted to 43% and the corresponding proportion of labor costs was now at least 50%, as shown in table 1.

Thus in the mid-Twentieth century began Phase 2, a new cycle in the volume-price loop. This time it was information technology which was the driving force. With mounting information labor costs providing the economic incentive, large research and development resources were redirected from the creation of production technologies to those which process, store, transport and manipulate information.[20] These investments resulted in dramatic improvements, as described earlier, in the availability, cost, and performance of technology to support information management. Porter and Millar observe, "The cost of computer power relative to the cost of manual information processing is at least 8,000 times less expensive than the cost 30 years ago. Between 1958 and 1980 the time for one electronic operation fell by a factor of 80 million."[1A]

As with production technologies in Phase 1, declining costs created a substantial increase in demand. This consequent rise in demand for information technology by U.S. business is indicated by the second curve in Figure 7, which shows the rise of information technology costs as a percentage of total technology expenditures during Phase 2. (The relevant data is presented in Table 2). Thus, the period since the late 1950s has seen the introduction on a massive scale of machines for processing, storing, and communicating information. These machines include computers, telecommunications systems, mechanical and electronic file handling systems, duplicating machines, word processors and a wide range of other office equipment.

Phase 1, beginning in the nineteenth century and lasting until just after the half way mark of this century, was the era of mass production. The critical technology was production machinery, which greatly increased the scale of output of industrial enterprises, leading to growth in the average firm size, and the emergence of large clerical bureaucracies to handle the paperwork within these firms. Phase 2, beginning in the 1950s and lasting until approximately the end of the 1980s saw the introduction of information technology. Mass production continued but was accompanied by computerisation of the office functions in organisations. Information technology led to the mass handling of transactions, marketing, and internal organisational control. During this period average firm size has remained relatively stable. The main driving forces and manifestations of Phases 1 and 2 are summarised in Table 3.

The United States economy has recently reached the point where expenditure on information technology exceeds that on the traditional industrial or production technologies. The fact that business enterprises now spend as much on the equipment that supports the manipulation of business information as on the machinery and equipment on which it has depended for the last century and more for all aspects of industrial production is striking evidence of the central role now played by information processing in the economic system.

We may ask why it was that Phase 2 progressed as rapidly as it did, requiring only some 30 years to reach the point at which we are now, when the transformation of production technologies characterising Phase 1 took a century or more. The answer lies in the description we have already given of the homogeneity of information handling processes in the economy, which contrasts with the heterogeneity of their counterparts in the production sectors. The speed with which the virtuous economic loop acts on technology costs depends on the volume of applications to which a given technological development can be applied. Since in Phase 2 the application of information technology was restricted to office environments, rather than factories or other non-information handling situations, very large demand for the technology was assured. The pool of functions carried out by office workers was much larger than that which had awaited automation during the period of Phase 1.

Now that both production and information technologies have experienced, as stand-alone technologies, the benefit of this virtuous economic circle, the conditions are right for the emergence of Phase 3. We call this the phase of integration. Like the previous two phases, it is characterised by the development of a new set of technological capabilities. These are the capabilities to combine information technology with the production and distribution of goods and services. In Phase 3 there is a reversal of the traditional distinction between production and information handling tasks.

There are at least three factors combining to create economic incentives for integration. First, the potential for cost reduction in the office is declining as automation of stand alone information handling tasks matures. Cost savings must come from new applications of the technology. Second, as the cost of information technology continues to decline, new, more complex applications requiring integration become feasible. Finally, improvements in the technology have made the bundling of information in products and services a critical strategic objective in many industries.[2A]

These incentives are encouraging the development of certain new technological capabilities in the areas of networking, standard interfaces, and telecommunications infrastructures. All of these technological developments are essential for integration.

And, although they are costly to use at first, reductions in cost follow as experience increases; this further increases demand and opens up new opportunities for the use of integrating technologies. The history of technology development indicates there will be a relatively rapid decline in the cost of computers manufactured with standardized interfaces - hence the desirability of standardization initiatives such as Open Systems Interconnection (OSI).

The process of integration has two dimensions: integration of information technology with production technology, linking the office and the factory, and integration of transactions internal to a business with those external to the business.

Integrating Office and Factory

During Phase 2, information technology was used almost exclusively to support information rather than production labor. In other words, computers and telecommunications equipment were used by office workers rather than factory workers.[21] Why did clerical automation precede factory automation, and why are we now ready for the latter? We can gain some insights into these questions by inspecting the trends in Figure 7. The development of low-cost computing technology was driven by the presence of vast untapped demand for information processing machinery to perform very homogenous tasks common to all office environments. In other words, the rise of information technology (Phase 2) would not have occurred without growth in information labor (Phase 1). Now that the huge volume of general purpose office applications (e.g. data, word processing, and file handling) has brought the costs of information processing devices to sufficiently low levels, these devices can be applied to the less uniform - more heterogeneous -applications on the production side of the economy.

The 1960s and 1970s were characterized by the automation of clerical tasks. Electronic automation of the factory began in the Eighties and will be a feature of the Nineties and beyond.

Figure 8 illustrates the changing relationship between information management and production as the technology has evolved. In Phase 1, the information management functions within firms began to grow and they became separate from production activities, but were not yet subject to mediation by technology. In Phase 2, information technology permeated the information management functions within individual businesses, but they did not cross the boundary between the firm's management and production activities. In Phase 3, the integration phase, information technology will permeate the linkages between the different boxes in Figure 8. In his book Manufacturing for Competitive Advantage, Gunn summarizes the situation saying: "Generally, we hear about the factory of the future or the office of the future as if there is a great wall between them.... Aren't we really talking about the business of the future? ..."The task that lies before us in manufacturing is only a small part of the far larger evolution (or revolution!) of computer integrated business...."[4A]

The integration of factory and office functions has two major strategic implications. First, it makes possible the transition from traditional mass manufacturing to what might be termed "programmed production." Other terms which have been used to describe this phenomenon are flexible specialization, customized automated production, and post-industrial manufacturing.[5A]

In this new mode of production, manufacturing continues to be highly automated, as it has been under mass production techniques, but the reprogramability of machine tools or robots allows the tailoring of product or services to individual users' requirements. Customizing an individual product or service more precisely to the needs of a given buyer presents new opportunities for achieving competitive advantage. One example of this new mode of operation is found in the semiconductor industry where programmed production has emerged as an important strategic concept. In another case, BMW installed a "smart" manufacturing system which allows it to build cars with their own tailored gearboxes, transmission systems and interiors on a normal assembly line.[6A]

The second strategic implication of office/factory integration is that it will become increasingly difficult in Phase 3 to distinguish between information and production technologies, nor will it be practical to distinguish between information and factory labor. This trend is suggested by Figure 7; because of the nature of the integration taking place, it will no longer be meaningful to measure information technology as a proportion of total technology, nor information labor as a proportion of total labor.

This traditional distinction between white collar and blue collar workers has already begun to break down. Is an operator in a largely automated factory to be classified as a computer programmer (information worker - white collar) or as a machine operator (production worker - blue collar?) Is a robot an item of information technology or production technology?[7A]

The evolution of programmed production is inevitable because of economic forces driving technological developments and changes in the structure of business. But there is already evidence that integrating the office and factory and moving from high volume assembly line production to lower volume customized production will be a painful process, as different industries and countries adopt the technology at an uneven rate. Reich summarizes the U.S. situation and makes it clear that moving to this process will not be easy, saying:

"...Flexible system processes cannot be simply grafted onto business organisations that are highly specialized for producing long runs of standardised goods. The premises of high volume, standardised production - the once-potent formula of scientific management -are simply inapplicable to flexible system production.

...Some U.S. firms are adopting flexible system production, but they are very much in the minority, far short of the proportion required for any kind of truly national adjustment. ...Flexible production is so fundamentally different from standardised production that the transition requires a basic restructuring of business, labor, and government; any reorganisation of this magnitude threatens vested economic interests and challenges established values and is thus bound to be resisted. ...As we shall see, the transition also requires a massive change in the skills of American labor, requiring investments in human capital beyond the capital of any individual firm".[8A]

The human obstacles in the path of such change have also been noted by Gunn:

"While it is literally and technically true that no one can buy or has a complete CIM [Computer-Integrated Manufacturing] or world-class manufacturing system, it is possible to get 80 to 90 per cent of the way there with the technology available today. Yet, most companies haven't gotten even 25 per cent of the way....Time and again, the major impediment to implementation...is people: their lack of knowledge, their resistance to change, or simply their lack of ability to quickly absorb the vast multitude of new technologies, philosophies, ideas, and practices that have come about in manufacturing over the last five to ten years".[3A]

Despite these difficulties, there are clear signs of progress in the transition form automated offices to integrated automated businesses. The obstacles we have noted must not be underestimated, but their effect will be to slow down rather than block the transitions predicted here.

Integrating Across Organisational Boundaries

In addition to the integration of office and factory technologies, the other dimension of integration which characterises Phase 3 is the extension of information systems beyond organisational boundaries. During Phase 2 information technology was applied almost exclusively to the automation of activities internal to a business. Computers and telecommunications networks were used to automate the internal generation of invoices, cheques and other financial records, and to automate internal control of inventory or stock movements. Once prepared, transfer of information records between the business and its suppliers and customers was usually effected by traditional manual means such as use of the mail. Direct linkages between the computer facilities of different organizations - which allows full automation of a transaction between two parties - have been rare. While very extensive networks linked the data processing centers within large organizations, the only electronic connection between businesses has usually been the telephone service.

The fastest growing segment of interorganisational networking is in the area of electronic data interchange (EDI), the computer-to-computer exchange of formatted business documents such as purchase orders, invoices, and way bills. In the late 1980s, EDI has become a major factor in customer/supplier relationships in the transportation, grocery, and automotive industries, and it is rapidly taking hold in other fields such as chemicals, electronics, financial services, and government.[9A]

The transportation industry was the first to adopt the EDI concept as a way of coordinating its business. Today more than 80 per cent of railroad waybills are sent electronically. An industry-wide network allows exchange of invoices, purchase orders, freight claim information, and so forth. The system improves fleet management and scheduling by allowing companies to know the exact location of their rail cars every day.

The grocery industry has probably benefitted most from interorganisational electronic links. Today about 25 per cent of all transactions between manufacturers, distributors and retailers are handled by EDI. For example, one large grocery wholesaler has reduced its inventory costs by $2 million annually, using the electronic network to order products closer to when they are actually needed. The wholesaler also estimates savings of more than $100,000 a year on the processing of purchase orders.[10A]

Major U.S. auto manufacturers now use EDI to exchange information on production schedules and ship notices with hundreds of suppliers. These networks help support just-in-time inventory management systems, which dramatically reduce inventory costs by closely coordinating the suppliers' deliveries with the manufacturers' production schedules. The auto makers have also begun requiring - not requesting - that their suppliers accept electronic invoices. Auto manufacturers in Europe are also now establishing electronic links to suppliers, customs authorities and transportation carriers to speed information flows and reduce the overhead of paperwork. IBM is planning EDI links to its 12,000 largest suppliers by 1991, developing external electronic networks. One IBM vice president commented, "Doing business without EDI will soon be like doing business without a telephone."[12A]

Finally, a major force behind electronic integration of organisations will be adoption of EDI as standard practice by government agencies. The U.S. Department of Defence, for example, currently has electronic ordering links to about 50 companies, and has announced its commitment to expand these systems to other suppliers. One report concluded, "In the procurement area, DOD handles about 30 million communications with 300,000 suppliers annually, as well as generating over 700 million internal transactions. ...Major suppliers...will be under pressure to establish standardised EDI links with DOD, and the ripple effect of such a DOD policy upon the procurement operations of other governmental departments and vendors could be tremendous."[11A]

In addition to the trend towards EDI, there is other empirical evidence that the economy is shifting the focus of its resource expenditures from internal information management tasks to more market-oriented external functions. Table 4 shows the way in which the balance of information management effort in U.S. businesses has been shifting since 1900. We can distinguish between information resources aimed primarily at supporting interaction in the marketplace and that directed towards internal management of the company. 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 organised units. The distinction is quite fundamental, in that the extent to which economic management is centralised 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 labor effort accounted for by the market as opposed to centralised mode of management. However, the data in Table 4 (bottom line) shows that the ratio of market-oriented to internal information management resources stayed within the range 0.96 to 1.25 between 1900 and 1960, and then jumped sharply to 1.65 by 1970. Comparable analysis of data for 1980 presents some difficulties due to a change in occupational definitions, but the ratio is continuing to rise. This suggests an ongoing trend towards market-based coordination of transactions - consistent with a reduction in average firm size.

Telecommunications networks

One of the reasons for the lack of integration during Phase 2 has been the lag in provision of public telecommunications facilities. By comparison with the path of economic structural development mapped out in Figure 7, the provision of public telecommunications facilities is delayed by some decades. The public telecommunications infrastructure appropriate to Phase 1 was the voice telephone network; it is primarily information workers, not production workers, who use the telephone, and, historically, they used it for voice and not data. (In most businesses, there is approximately one telephone set per white collar worker and almost no provision of telephones for shop floor workers), In Phase 2, information workers had the assistance of information technology, and the corresponding telecommunications requirement began to include data transmission. Ideally, we would have seen the development of public voice telephone services in keeping with the growth of information labor in Phase 1 and of public data networks in keeping with the spread of information technology in Phase 2.

In fact, even though white collar work became extensive beginning with the end of the nineteenth century, telephones did not become commonplace in businesses until a few decades later. Near-universal penetration of telephone service was not achieved in most industrial countries until the 1960s and 1970s, even though the information workforce had become a very substantial component of the economy as early as the 1930s and 1940s.

The lag in the provision of public data communications facilities in Phase 2 is equally clear. By the late 1960s most major corporations were making substantial use of computers to automate at least some clerical functions, but interconnection between them was practically non-existent. Since there was a wealth of requirements for interconnecting data centers, corporations began to build private data networks linking their establishments. In the 1970s they were able to draw on the services of packet switch network providers to provide links between centers which did not justify a fully-dedicated private data link. However, to date, no country's telecommunications network operators provide the general business public with a switched data service which would provide data interconnection analogous to that available for voice (except through the very rudimentary procedure of sending data signals through a modem over a voice telephone link).

In view of this shortcoming in the communications infrastructure, it is not suprising that even now, toward the end of Phase 2, the overwhelming majority of all data communications takes place within rather than between organisations. The only inter-company networks of any significance which existed prior to the 1980s were those serving the banking and airline sectors, both of which had exceptional needs for worldwide interconnection of their data facilities. This is beginning to change, however, with the emergence during the late 1980s of some inter-company networks linking interest groups such as buyers and sellers in an industry, or retailers and banks in the case of financial transactions (Estrin, 198x).

Recognizing the very large potential for further exploitation of information technology once universal data interconnection of establishments is available, the telephone companies in the United States and their counterparts in other industrialised countries are developing plans for integrated services digital networks (ISDN), which will provide widespread data connections among general business users.[13A]

As with previous generations of the public telecommunications infrastructure, however, we can predict that the reality of universal data networks will lag far behind apparent market need. Technologies for external integration are appearing first as EDI, which will be an intermediate step before the development of integrated data networks. The speed at which interorganisational integration takes place will depend not only on the technology but also on the economic and competitive needs in particular industries. Just as certain industries, e.g., banks and insurance, led the way in automating clerical functions in Phase 2, other industries such as transportation and auto manufacturers are proving to be early adopters of integration technologies, as they become available.

Not only will the impacts of inter-company integration vary from industry to industry, but individual firms will find themselves confronted with a confusing array of strategic decisions about networking technologies, as described by Keen:

"The concept of "integration" in telecommunications and computers is elusive and at times rather like an advertising slogan, "New and improved." From the perspective of the senior manager, the issue is not integrated technology but integrated customer service. What range of services can the customer get access to from a single workstation?

...It is far cheaper and easier to design a network capability that provides specific services than one that plans ahead for full integration. It may...be that customers do not need integrated financial services, integrated software that combines spreadsheets, word processing and database management, or integrated terminals. Or they may. When? Why? The issue of the degree of integration that the architecture should provide for is again a business question that cannot be answered by forecasts, only by vision and the act of faith to make radical business moves."[14A]

Strategic Implications of Interorganisational Integration

The integration of internal and external transactions between firms will contribute to at least five strategic trends in Phase 3:

1. Integration inherently means businesses are more tightly linked to one another. For example, the onset of networking between buyers and sellers means that companies can provide their customers with direct access to internal data bases. Pacific Intermountain Express, a major trucking company, allows customers to access its computer files directly to check the status of their shipments, while American Hospital Supply electronically monitors the production schedules and inventory levels of its major suppliers to make sure they can meet the projected needs of the medical supply company.[15A]

In addition, external integration makes practical new business processes, such as just-in-time inventory control, reducing inventory levels by an average 15-20 per cent.[16A] In many cases, electronic integration will lead to shorter lists of suppliers for major customers who want to develop a few close relationships. Although not entirely attributable to integration, IBM's Lexington, Kentucky plant has reduced its number of suppliers from more than 700 to less than 45. Similarly, Xerox has cut its number of global suppliers from 5,000 to 370. This trend represents substantial cuts in clerical overhead needed to manage all these relationships.[17A]

The integration of information systems also causes sellers to become more service-oriented, using information networks to reach and service their customers. Ford has enhanced customer service by providing a system that allows its dealers to access each other's parts inventories to more quickly locate parts needed for repairs.[18A] Meanwhile, a chemicals company shifts the basis of competition from just price to more of a service orientation by giving its customers microcomputers to directly access its mainframe. Customers use the system to decide on product mix and order frequency, as well as for direct order entry.[19A] This trend toward increased service orientation is clearly complimentary to the emergence of programmed production mentioned earlier, since it allows immediate and precise response by the production system to a change in the customers' needs.

2. Computer integration will not only provide faster, more efficient information exchange between firms, it will also create fundamental changes in market structures. Interorganisational integration will have different effects on different industries and, in many cases, it will lead to the evolution of electronic markets for buyers and sellers. There is growing theoretical and empirical evidence that the ability of information technology to reduce coordinating costs will increasingly encourage the use of markets, instead of hierarchies to coordinate activity.[20A]

Airline reservation systems are a classic example of the growth of an electronic market made possible by information technology. In another case, Western Union created an electronic market that matches freight shippers with motor freight carriers. Western Union adds value for the shipper by verifying the carrier's legal authorisation and insurance coverage.[21A]

The trend towards electronic markets is encouraged by two capabilities of information technology. Improved communication capabilities - the ability to access more complex information faster - makes it feasible to describe many more products to potential customers over electronic networks. In addition, programmed production technologies make it practical for firms to shift from producing one product to another in response to market demand. This type of flexible manufacturing means customers are likely to find an increasing number of suppliers trying to respond to their needs, thus creating fewer permanent, hierarchical buyer/seller relationships.[22A] Networking technologies will in many cases lead to a level of integration that builds economic incentives for coordination in the form of electronic marketplaces.

3. The emergence of global communication networks encourages the transition of worldwide firms from multinational to transnational modes of operation, extending the geographical reach of firms into new markets. Dow Jones, for example, now pursues a more global strategy publishing Asian and European editions of the Wall Street Journal. The Journal has become a true national and international newspaper due to electronic communications capabilities that allow it to distribute editorial content to printing plants worldwide.[23A] In another example, IBM can manufacture products on a global basis because of an electronic network that links about 55 plants and design centers around the world. As a result, any engineering change can be sent to all 55 plants electronically in seconds.[24A]

4. There are many markets where the development of integrated data networks will affect both the market structures and the products being sold. This will be particularly evident where the product itself is information rather than a physical good. Industries ranging from publishing and broadcasting to all aspects of retail and commercial financial services will be affected. In these businesses, the much improved communications networks, which will characterise Phase 3, will radically change the way products are delivered.

One firm that has redefined its role in the information business to take advantage of electronic integration is Reuters, the London-based news-gathering service. Reuters developed a computerized information retrieval system that gives clients direct access to the latest prices from financial, oil, commodity, and other international markets, as well as providing instant access to financial and general business news.[25A] Reuters' clients now have terminals in more than 24,000 locations in 160 countries.

In some cases, networking technology is dramatically reshaping industries. For example, the Publix supermarket chain in Florida turned its cash registers into point-of-sale banking machines, using its customer contact and ownership of a sophisticated telecommunications network to force major banks to cooperate in its new venture.[26A]

Integration breaks down walls between industries. Suddenly retailers and oil companies are moving into banking, banks into publishing, and customers into suppliers' functions. The concept of delivering multiple information-intensive services and products through the same terminal is what makes this feasible. And where time and information represent key product differentiators or open up new market opportunities, those with electronic networks have the chance to gain significant competitive advantage.[27A]

Electronic marketplaces will evolve in many instances, with communications networks being used not only to accept orders, fulfill transactions and so forth, but also to effect delivery of the goods themselves. The very large investments currently being undertaken by financial institutions in communications and information processing technologies is one symptom of the transformation which is going to affect the structure, behaviour, and performance of the markets for information-intensive products.

5. Finally, there is growing evidence to support the theory that integration will lead to a reduction in average firm size. The hypothesis that information technology will affect market structure because of its impact on the process of coordination among firms has been subject to increasing theoretical study and mathematical modelling work. The findings must still be considered tentative but Malone (198x) and Oniki (1987), among others, have explored the relationship between the changing costs of coordination and the impact on firm size. Although the models used by these two researchers are different, their broad conclusions are the same: the adoption of information technology tends to result in an increase in decentralisation of the economy, and a reduction in average firm size. This result applies even if information technology reduces both internal and external coordination costs.

We noted earlier that there will be obstacles to this transition, chiefly as a result of the understandable rigidity and inertia of human organisations. We must also expect that not all progress in the directions indicated by this prognosis will be beneficial, either to the individual businesses involved or to society as a whole. However we can predict with some confidence that the changes we have forecast in connection with the transition to Phase 3 will take place. This is because they are consequent on underlying economic forces which are difficult, in the long term, to resist. In the same way that the automations of routine computational and file handling functions within offices became almost complete during Phase 2 despite organisational and human resistance, we can expect progress in the direction of integration (as defined in this paper) to accelerate during the early years of Phase 3.

In summary, Phase 3 of the information technology revolution will bring about changes qualitatively different from those which characterised the previous two phases. Electronic technologies will not just be adopted in larger numbers; they will be used to restructure businesses. The emphasis will be on improvements in the quality of products and services delivered, rather than on improving the efficiency of selfcontained information-handling operations. This will in turn require the adoption of information technologies which integrate previously separated domains of automation -the office and the factory, and one business with the next.

The fact that we are entering a Phase 3 which is qualitatively different from Phase 2 justifies both the investments being made by corporations in upgrading their information systems to cope with the new phase, and the investments being made in public telecommunications infrastructure (especially digital networks) to serve the emerging requirements. Both these activities are being pursued with considerable vigour even without the benefit of systematic economic analysis or justification. Business organisations are planning for an era in which the ability to compete by taking advantage of all the capabilities of information .technology is a key criterion of success. Telecommunications and computer companies throughout the world are laying the foundations for digital networks. There is some vagueness in the minds of both parties as to just what the nature of this new competition will be, why information system networking is a critical element of it, and why it has not been so important in the past. In this study we attempt to understand the rationale behind this new wave of investment. Why are businesses now seeing information systems as a key competitive weapon? Why are societies investing in a new generation of telecommunications infrastructure?

Clearly this paper is not intended to answer those questions in detail; circumstances will differ from industry to industry and application to application. What it tries to show is that, at the macroeconomic level, the transition from Phase 2 to Phase 3 has an economic logic or rationale in the same way that the transition from Phase 1 to Phase 2 did.

TABLE 1
EMPLOYMENT OF PRODUCTION AND INFORMATION LABOR
UNITED STATES, 1900-1980

YEAR	NUMBER OF PRODUCTION WORKERS (000'S)	NUMBER OF INFORMATION WORKERS (000'S)	RATIO OF INFORMATION TO PRODUCTION WORKFORCE
1900	23,835	5,196	0.22
1910	29,170	8,121	0.28
1920	31,434	10,771	0.34
1930	34,091	14,595	0.43
1940	35,367	16,373	0.46
1950	36,970	22,029	0.60
1960	36,916	27,621	0.75
1970	41,061	38,665	0.94
1980	46,620	52,683	1.13

Sources: Detailed Occupation of the Economically Active Population, 1900-1970. U.S. Bureau of Census, Historical Statisitcs Series D233-682; 1980 data from U.S. Bureau of Labor Statistics, Bulletin 2175, December 1983, adjusted for consistency with definitions in 1970 data

TABLE 2
EXPENDITURE ON PRODUCTION TECHNOLOGY AND INFORMATION TECHNOLOGY
UNITED STATES, 1965-1985

(CONSTANT DOLLARS, 1985 VALUE)

YEAR	EXPENDITURE ON PRODUCTION TECHNOLOGY (1985 US $ M)	EXPENDITURE ON INFORMATION TECHNOLOGY (1985 US $ M)	RATIO OF INFORMATION TO PRODUCTION TECHNOLOGY EXPENDITURE
1965	60,355	18,795	0.31
1966	66,955	22,529	0.34
1967	66,539	23,062	0.35
1968	62,157	23,219	0.37
1969	63,808	27,340	0.43
1970	63,449	28,568	0.45
1971	58,657	27,212	0.46
1972	62,993	26,778	0.43
1973	69,741	29,953	0.43
1974	74,523	31,321	0.42
1975	68,613	27,434	0.40
1976	77,258	32,311	0.42
1977	87,858	37,241	0.42
1978	98,290	42,863	0.44
1979	100,576	47,858	0.48
1980	96,725	52,053	0.54
1981	98,333	55,720	0.57
1982	81,080	56,791	0.70
1983	77,221	61,456	0.80

NOTES:

1. Data refers to expenditure by US business enterprises, adjusted by GDP price deflator.

2. Production Technology category includes:-
   Engines & Turbines; Agricultural Machinery except Tractors; Construction Machinery; Mining & Oilfield Machinery; Metal Working Machinery; Special Industry n.e.c.; General Indusrial, including Materials Handling, Equipment; Service Industry Machines; Electrical Transmission, Distribution, and Industrial Apparattus; Other Electrical Equipment.

3. Information Technology category includes:-
   Office Computing & Accounting Machinery; Communications Equipment.

4. Source: Survey of Current Business, various issues.

TABLE 3
THE THREE PHASES OF THE INFORMATION REVOLUTION

PHASE	MEASURES & TIMING	DRIVING TECHNOLOGY	MANIFESTATIONS
1. Growth of the Information Management	Ratio of information labor to production labor costs Passed 1:1 circa 1960 (U.S.A)	Production Machinery (Stand Alone)	Mass Production Growth of large clerical bureaucracies Growing average fiirm size
2. Growth of Information Technology	Ratio of information technology to production technology costs Passed 1:1 circa 1990 (U.S.A)	Information Systems (Stand Alone)	Mass production and mass marketing Automation of large clerical bureaucracies Stable average firm size
3. Integration	N/A	Integrated/ Networked Information/Production systems	Programmed production Electronic Markets Falling average firm size

TABLE 4
MARKET ORIENTED VERSUS INTERNAL INFORMATION MANAGEMENT EFFORT IN U.S. BUSINESSES (000'S OF PERSONS 14 YEARS & OLDER)

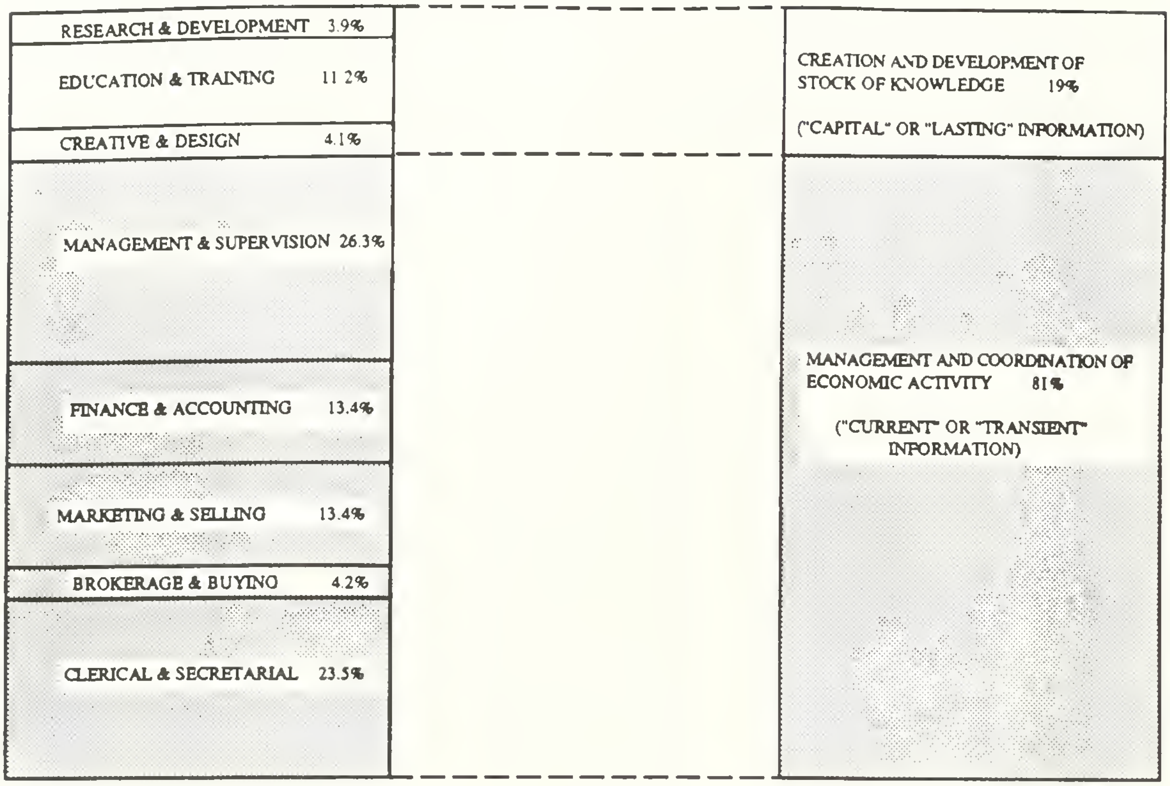
	1900	1910	1920	1930	1940	1950	1960	1970
MARKET ORIENTATED								
Accountants & Auditors	23	39	118	192	238	390	477	713
Buyers & Department Heads, Store	0	15	20	35	74	147	238	387
Credit Men	2	2	14	22	30	34	48	60
Purchasing Agents & Buyers	7	8	18	29	34	65	105	164
Agents (n e c)	25	28	64	102	73	128	163	***
Collectors, Bill & Account	34	36	31	43	45	24	32	53
Bookkeepers	174	336	462	553	541	746	936	1574
Cashiers	58	112	154	185	180	248	492	878
Ticket Station & Travel Agents	27	35	37	38	47	61	73	100
Shipping & Receiving Clerks	23	65	132	168	233	304	295	427
Advertising Agents & Salesmen	12	11	25	40	41	35	35	65
Auctioneers	3	4	5	4	4	6	4	5
Demonstrators	3	4	5	8	10	14	26	40
Misc Sales Occupations	77	80	50	57	55	24	57	122
Insurance Agents & Brokers	78	88	120	257	253	312	369	461
Real Estate Agents & Brokers	34	78	89	150	119	145	196	266
Stock & Bond Salesmen	4	6	11	22	18	11	29	99
Salesmen and Salesclerks	1089	1454	1724	2482	2893	3485	3888	4186
Total	1673	2401	3079	4387	4888	6179	7463	9600
INTERNAL MANAGEMENT								
Managers, Officials & Proprietors	1511	2135	2390	3113	3197	4419	4586	3756
Construction	58	183	107	199	175	296	378	397
Manufacturing	174	350	406	447	432	665	826	752
Transportation	66	82	83	98	90	151	159	164
Telecom, Utilities, & Sanitary Svs	6	19	25	39	54	68	108	115
Wholesale Trade	78	104	143	152	225	343	338	310
Retail Trade	930	1119	1220	1592	1620	1977	1628	1119
Other Services	199	278	406	586	601	919	1149	899
Managers & Superintendents, Building	0	32	43	71	72	68	54	85
Officials, Lodge,Society,Union Etc	0	8	12	15	26	28	34	51
Pesonnel & Labor Relations Workers	2	3	5	12	26	50	99	296
Foremen	162	318	485	551	585	867	1199	1618
Total	1675	2496	2935	3762	3906	5432	5972	5806
RATIO OF MARKET ORIENTATED TO INTERNAL MANAGEMENT	**1.00**	**0.96**	**1.05**	**1.17**	**1.25**	**1.14**	**1.25**	**1.65**

n e c - Not Elsewhere Classified

Source: Detailed Occupation of the Economically Active Population, 1900-1970, Bureau of the Census, Historical Statistics, Series D233-682.

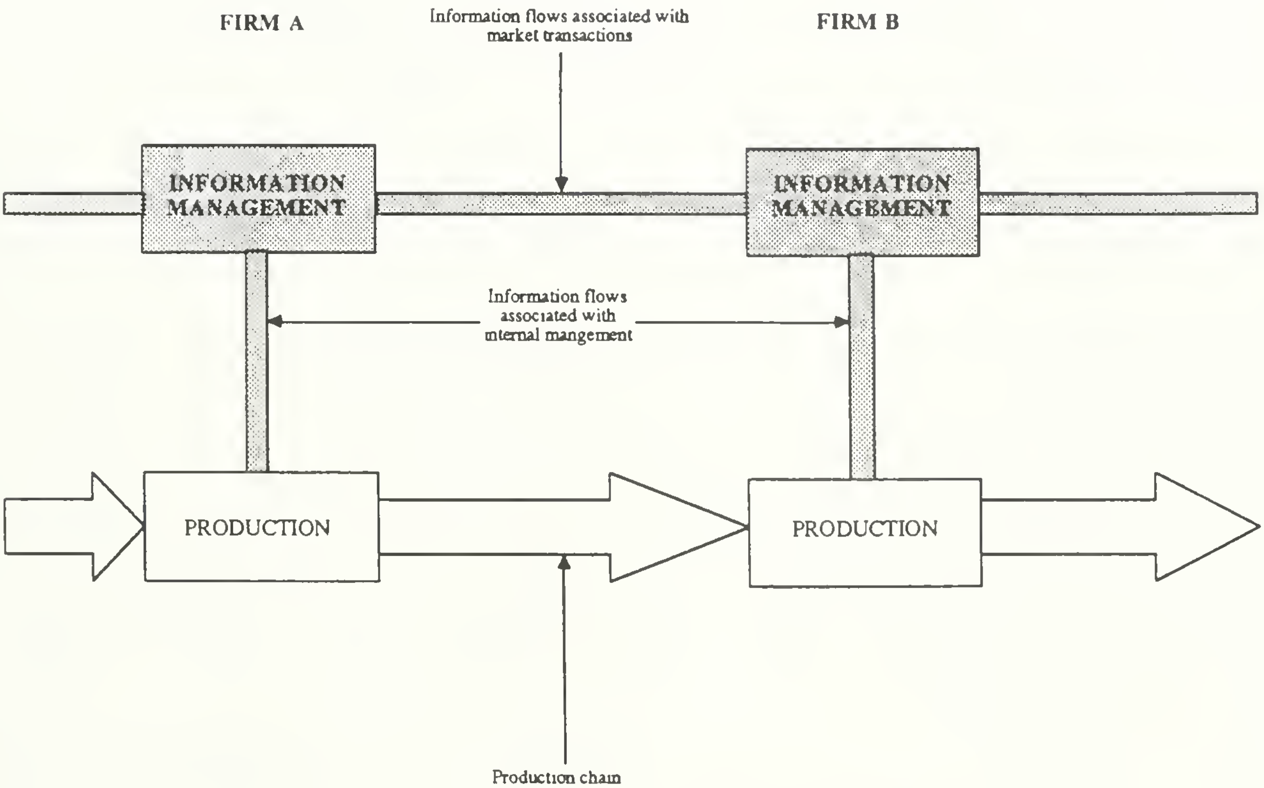
FIGURE 1
FUNCTIONS PERFORMED BY INFORMATION WORKERS.

PERCENTAGE BREAKDOWN OF USA INFORMATION WORKFORCE BY FUNCTION, 1990



SOURCE: Based on Bureau of Labor Statistics forecasts; occupational categories were assigned to the functions shown in accordance with the author's classification scheme for information workers

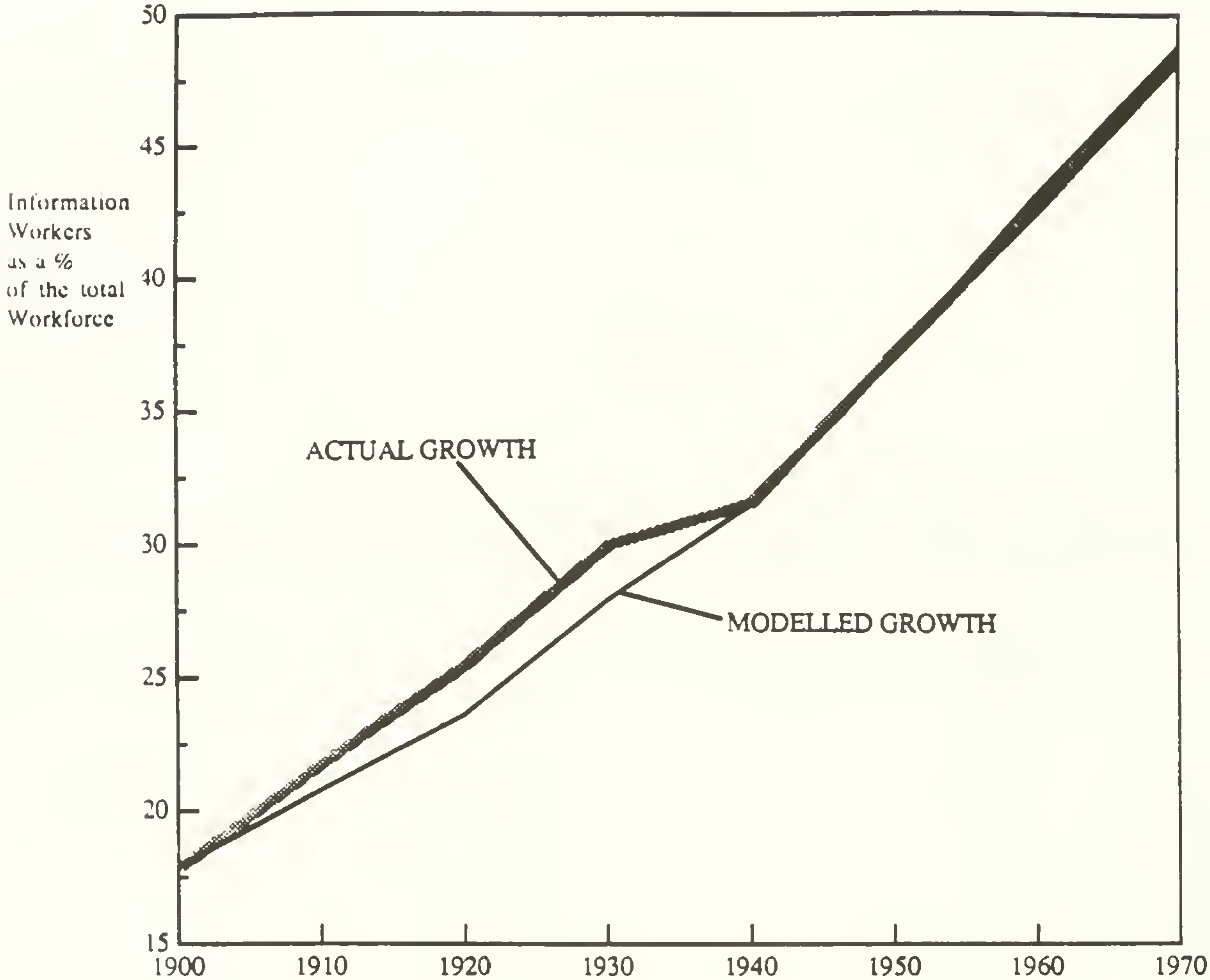
FIGURE 2
DIAGRAMMATIC REPRESENTATIONS OF THE INFORMATION PROCESSING ACTIVITIES ASSOCIATED WITH THE MANAGEMENT OF THE ECONOMIC SYSTEM



NOTES 1. For estimates of the magnitude of labor resources associated with the different elements of this diagram, see figure 1 and table 4.

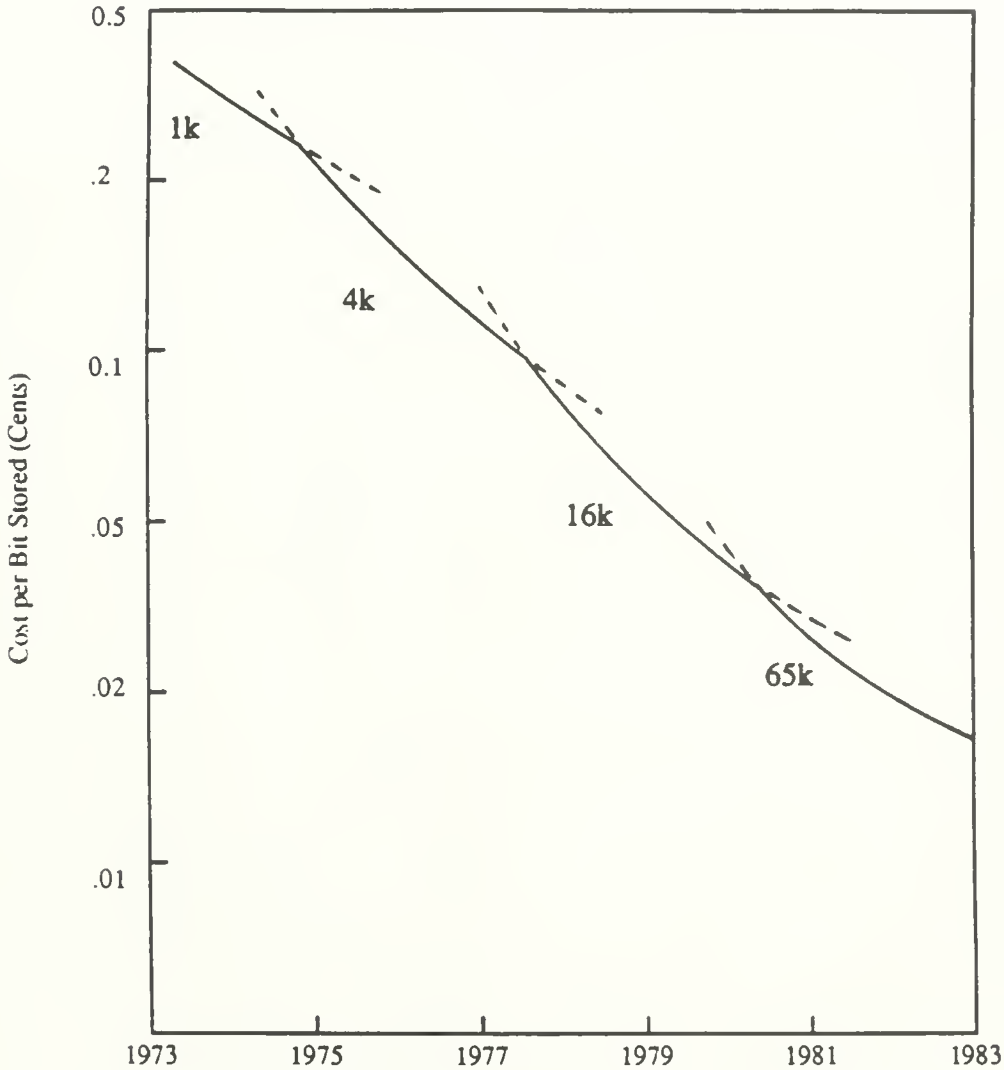
2. This is a simplified version of a more detailed model of information management in the economy described by Jonscher (1981)

FIGURE 3
GROWTH OF INFORMATION WORKFORCE DURING PHASE 1
USA,1900-1970



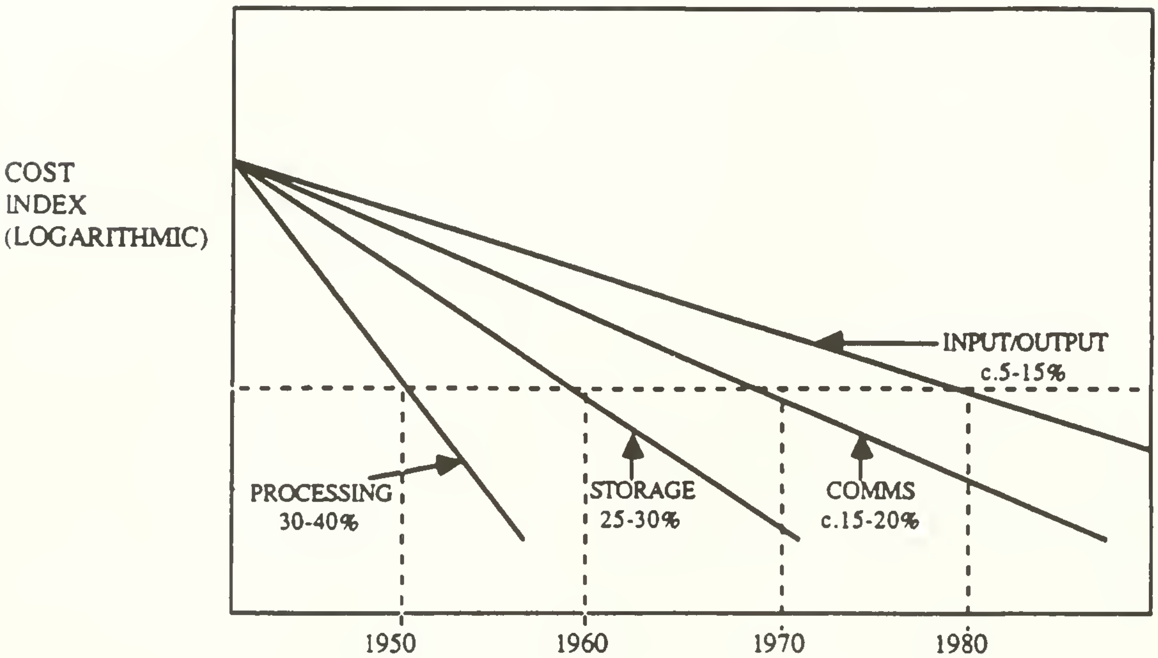
Source: Appendix A, Table A

FIGURE 4
FALL IN COST OF MICROELECTRONIC MEMORY DEVICES



Adapted from Noyce 1977

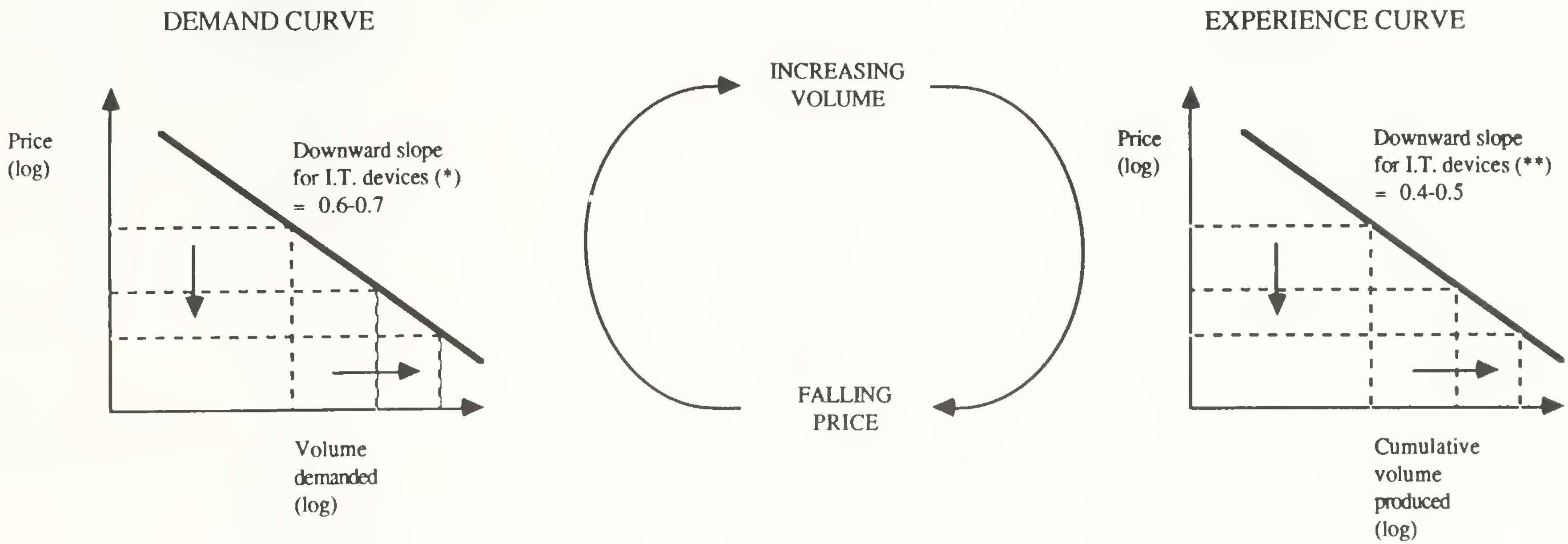
FIGURE 5
APPROXIMATE RATES OF COST DECLINE FOR FOUR INFORMATION HANDLING FUNCTIONS AND THE CORRESPONDING FOUR STAGES OF DEVELOPMENT OF INFORMATION TECHNOLOGY APPLICATIONS.



STAGE	1	2	3	4
TIMING	1950'S	1960'S	1970'S	1980'S
PRINCIPAL NEW APPLICATION AREA	Scientific/ Mathematical	File Handling	Remote Working, Networking	Personal Computing
PRINCIPAL NEW COST COMPONENT	Processing	Storage	Communication	Input/Output

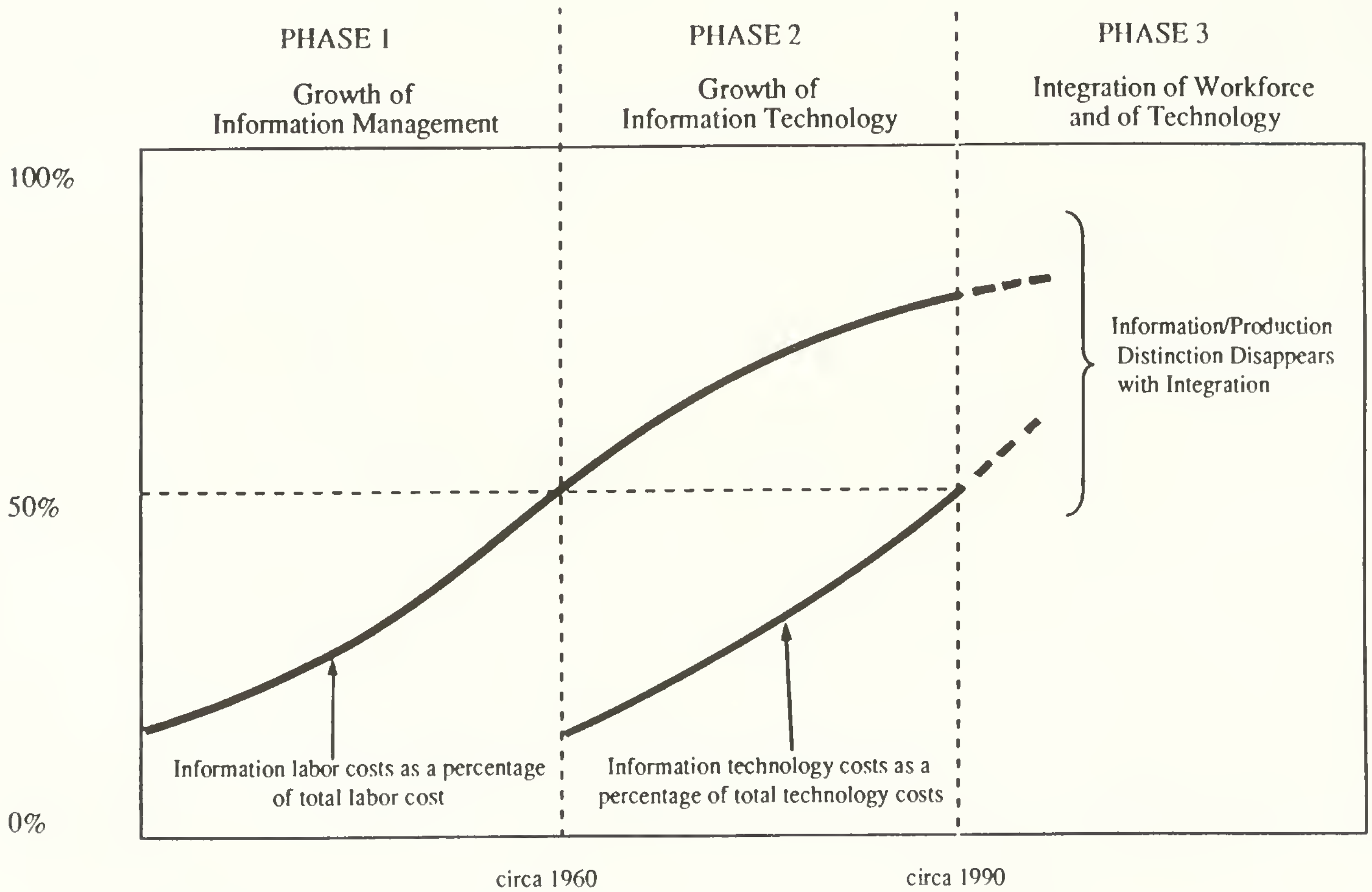
Source: See Text

FIGURE 6
THE "VOLUME-PRICE LOOP" IN THE ADOPTION OF INFORMATION TECHNOLOGY



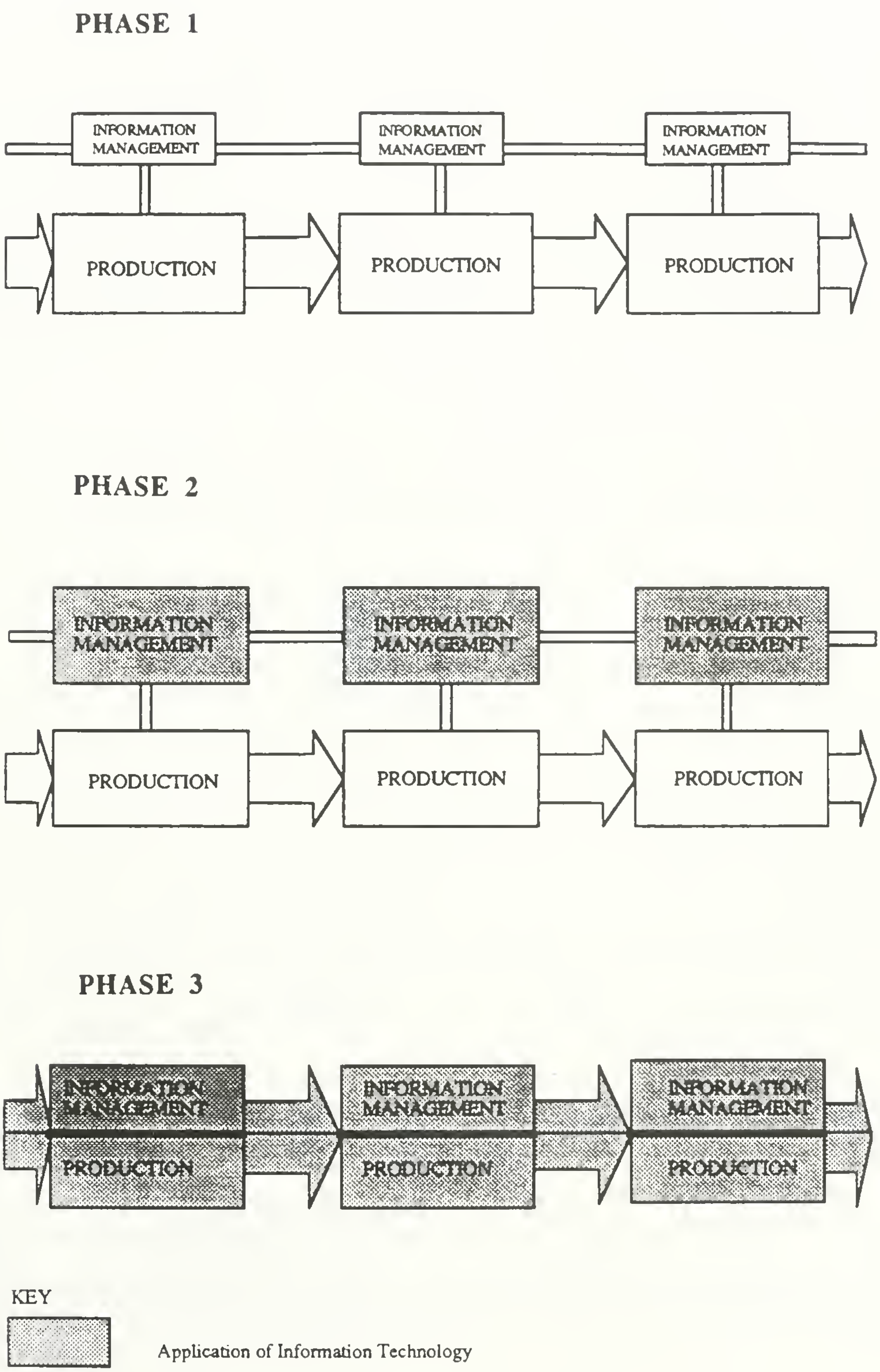
Note: (*) Corresponds approximately to a 35% drop in price for each doubling of volume demanded
(**) Corresponds approximately to a 25%-30% drop in price for each doubling of volume produced

FIGURE 7
THE THREE PHASES OF THE INFORMATION REVOLUTION



Notes: For data on information labor and technology see Tables 1 and 2.
All data refers to USA private business enterprise.

FIGURE 8
THE PATTERN OF ADOPTION OF INFORMATION TECHNOLOGY
PHASES 1,2 AND 3.



FOOTNOTES

1 Machlup (1962) was the first to measure the extent of allocation of resources to the creation of knowledge as opposed to other kinds of products and services. Other analyses of this kind were carried out by Porat (1977) and again by Machlup (1980).

2 This is taken from Jonscher (1983). Measurements of the information handling resources of other industrialised countries have been compiled by the Organization for Economic Cooperation and Development (1981). For a discussion of information labor trends in Japan and the UK see also Ohira (1987) and Gleave, Angell and Woolley (1984) respectively.

3 During the late 1970s and early 1980s, many governments took the first steps towards establishing an information technology policy. In the United States, the National Telecommunications and Information Administration (NTIA) was established within the Department of Commerce, and was charged with developing a broad approach to information and communications policy in that country (see for example NTIA, 1981). Under the Thatcher government, the United Kingdom Department of Industry embarked on a series of studies of the information and telecommunications industries, and appointed a Minister of Information Technology to take overall responsibility for this sector of the economy. President Giscard d'Estaing of France commissioned a wide ranging report entitled "The Computerisation of Society" (Nora and Minc, 1977). In addition to similar initiatives in a number of its member countries, the Organisation for Economic Cooperation and Development (1981) carried out a series of systematic studies of the impact of the emerging information technologies and industries on employment, productivity, investment and growth.

4 Fritz Machlup has produced the most thorough classification to date of writings on the economics of information and knowledge, to be published posthumously by Princeton University Press as volume three of his planned ten volume study: <u>Knowledge: Its Creation, Distribution and Economic Significance.</u> His scheme contained the following 17 main headings: (1) The economics of knowledge and

information: general; (2) The production and distribution of knowledge: knowledge industries, information services, information machines, (3) Ignorance, chance, risk, and uncertainty as factors in the explanation of individual choices and particular economic institutions and phenomena; (4) Uncertainty, risk aversion, venture spirit, innovativeness, and alertness as factors in the explanation of entrepreneurship and profit; (5) New knowledge (invention, discovery) and its application (innovation, imitation) as factors in economic growth; (6) The transfer of technology and know-how; (7) Economic forecasting; (8) The cost and value, private or social, of information and alternative information systems; (9) Decision theory and game theory; (10) Decision-making by consumers with incomplete and uncertain knowledge; (11) Decision-making by workers and job-seekers with incomplete and uncertain knowledge; (12) Decision making by private firms, in various market positions, with incomplete and uncertain knowledge; (13) Policy-making by governments and public agencies with incomplete and uncertain knowledge; (14) The formation and revision of expectations and their role in economic dynamics; (15) The role of information, knowledge, expectations, risks and uncertainty in the functioning of markets and the formation of prices; (16) Prices as an information system for resource allocation and product distribution in market economies and planned economies; national programming and planning; (17) Human capital: the accumulation of knowledge and skills

5 For reviews of this area see Arrow (1980) and Lamberton (1984).

6 Why do the special features of what we have described as the economics of symbol manipulation, rather than the special features of the economics of knowledge, provide the key to understanding the causes behind the information revolution? The answer is implicit in figure 1 (which is discussed later in this paper). For those information activities which produce knowledge of a lasting or "capital" value, the problem of resource allocation concerns, typically, the amount of resources which should be devoted to the production of the knowledge in question, and the number of agents who should be recipients of that knowledge. These resource allocation issues arise in the case of research and development expenditures (given the tension between the desire to provide incentives for funding research and development on the

one hand, and the desire to make results available to all who could benefit from it on the other, what should be the period of protection granted by patent law?) and in the area of creative arts such as the production of programs for mass entertainment (where an analogous tension arises). However figure 1 indicates that the resources allocated towards this kind of information creation (as measured by occupational breakdown of the workforce) accounts for only one fifth of the information handling expenditures in the economy. The remaining four fifths are concerned with the routine handling of information of transient value. It is clear from inspection of the occupational descriptions of persons involved in these latter categories of information handling that the "public good" characteristics of knowledge as a commodity are of little concern. The people - buyers, sellers, clerks, administrators, typists - are not producing knowledge which should be patented or copyrighted and then licensed or sold to one or more other potential users. The tranformation we are seeing in the role of information in the economy is due primarily to the way in which technology is transforming these routine information handling processes.

7 For example, the cumulative output was about 3 million units in 1964 and 2,000 million units by 1972.

8 The current state-of-the-art size of random access memory in a single integrated circuit for commercial production is 1M (1,048,576); larger capacity devices are under development.

9 This is the estimate of the Boston Consulting Group (1968), based on data published by the Electronics Industry Association. Noyce (1977) arrives at a figure of 28%.

10 Optical transmission of information (through optical fibers) is now widespread, but these systems remain electro-optical in the sense that electronic components are required at each end of a link and at all amplification points. Optical processing is still in its infancy.

11 For a very thorough discussion of the history of manufacturing costs of data processing systems, see Phister (1979), part I.4.1 (Supplement). This covers not only

the main functional categories of component such as processing, memory etc., but also miscellaneous cost elements such as power supplies and mounting hardware (printed circuit boards, cabinets). Other historical sources used in this study include Rudenberg (1969), and A.C.T. (1977).

12 Proprietary data prepared by Frost and Sullivan.

13 The original data has been adjusted as necessary to ajust for the effects of inflation.

14 However estimates range from as high as 24% (Phister, 1979) to as low as 10% (proprietary data from the Diebold Group), depending in part on the bundle of communications services which form the basis of the analysis.

15 See also extensive data in Phister (1979).

16 The case of communications costs is complicated by the fact that communications facilities are, in the main, provided as services by third party industries rather than as products, and that the industries providing them have not operated in normally competitive markets. Both these aspects of communications service provision are undergoing change (see, among several other texts, Tyler, Jonscher and Watts, 1988).

17 The categories included under our definition of technology do not include all items of capital expenditure as defined by economists. Both production work in industrial establishments and information processing work in offices is accompanied by capital expenditures which are not on machinery or equipment - items such as factory buildings and sites in the case of industrial work, and office buildings and furniture in the case of information handling work. We have also excluded expenditure by consumers on technology items, which, again, falls into both information processing categories (as in the case of television sets and home computers) and non-information processing machinery (such as dishwashers and kitchen appliances).

These results confirm the value of policies which encourage reductions in the cost to users of information processing and communications equipment and services. An obvious example is the recent progress in introducing greater competition in telecommunications in many countries. Regulatory decisions to introduce greater competition into telecommunications equipment and service markets are undoubtedly contributing to the continuing decline in price of business use of telecommunications services (see Tyler, Jonscher and Watts, 1988). As such, they appear by our analysis to be contributing significantly to overall productivity growth.

18 These impacts on resource demands have been calculated by dividing each of the value share coefficients in the left hand column of Table B4 by the corresponding value share of that input in total output in 1983.)

19 Wage data for different occupational categories are given in the Statistical Abstract of the United States, table no. 386, "Median Annual Earnings of Civilians, by Sex and by Occupation," various years.

20 In the 1950s, xx% of research and development expenditures in the United States were spent by industries which we would characterize as information technology. By 1970 this proportion had grown to xx% (Oettinger, 19xx).

21 In 1985 United States business spent $xx billion on office information technology and only $xx billion on informatoin technology equipment for the factory environment (Source: ______________). Therefore 9x% of total information technology investments can be attributed to the support of office rather than production labor.

23 The transistor was invented at Bell Laboratories, the largest corporate research facility in the world. That the American Telephone and Telegraph company had the largest research budget was a consequence of its own great size as a company, stemming in turn from the fact that it was supplying facilities - specifically, telephone facilities - to the generality of information workers, rather than to a specific functional or industry group.

This is a clear example of the causal chain from economic pressures (in this case, scale of demand) to the direction of technological innovation. We are not suggesting, however, that in general only large companies develop and exploit important inventions. For extensive research on the relationships between innovation and market structure see for example the work of Mansfield (19xx).

ADDITIONAL FOOTNOTES

1A Michael E. Porter and Victor E. Millar, "How Information Gives You Competitive Advantage, Harvard Business Review, July-August 1985, p.152.

2A See Porter and Millar.

3A Thomas G. Gunn, Manufacturing for Competitive Advantage, (Cambridge, MA: Ballinger Publishing Co., 1987), p.153.

4A Gunn, Ibid., p.207,213.

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