Technological Change and Technical Innovation in American Microelectronic Industry: An Introduction

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1.-Introduction

The analysis of technological innovation, to be really useful, requires to be based on a detailed framework including the crucial technical aspects, the barriers they impose to development, the challenges they forced to overcome and the solutions that finally solved the problems in a changing economic conext; this is specially true in the microelectronic industry. Some of these issues are analysed in this introducting paper.

2.-A science-based invention, a goal-oriented research: the transistor

The invention of the transistor is a clear case of science-based invention: it was a better theoretical and experimental knowledge of electric properties of solid state that made it possible. This happened with the point-contact transistor, invented by Bardeen and Brattain (1947) but it was specially neat in the case of the junction transistor, described by Shockley two years before the device was constructed (1951).

This scientific understanding, certainly, had the opportunity to process a lot of previous technological data and experiences coming from the radio and radar industries.

On the other hand, the invention was not the result of a random search but, on the contrary, the successful outcome of a goal oriented research developed at the Bell Laboratories. [1]

The history of the invention itself has been described several times; therefore, I will focus the exposition on other issues directly connected with the main topic. [2]

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[1] "By the end of the Second World War, pure research had provided sufficient information to make goal-oriented approach worth while. The approach at Bell Laboratories was still fundamental in that they did not empirically tinker with dvices, but tried to understand at each step what was going on. But their approach was goal-oriented: they knew what they wanted and went looking for it", E.Braun and, S, Mac Donald, Revolution in Miniature, Cambridge University Press, Cambridge, 1978, pg 9.

[2] -See next page.

3.-Product design and manufacturing process

Transistor would not have had the impact it has been if the invention of the product had not been followed by the invention and the development of new product's design and of suitable manufacturing processes for mass production.

The vacuum tube industry had in the already existing light bulb industry and in its manufacturing processes and important source of ideas and experiences which were of direct value. No similar continuity existed in the case of the transistor; it was therefore necessary to set up a new industry in the strong sense.

The first transistor -the point-contact- was substituted because of its manufacturing difficulties and low efficiency; the junction transistor was more efficient and also more suited for mass production. Nevertheless, in the early fifties, the output of the production line was not really under control, the product was not standardized.

This situation changed in the early sixties with new designs and new processes, as the silicon transistor, [3] (made by Texas Instruments in 1954), the diffusion process, the utilization of photographic techniques and the planar process, among others. This

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[2] -Seem among others:

-Ch. Weiner, "How transistor emerged", IEEE Spectrum, january 1973.

-W. Shockley, "The Path to the conception of the Junction Transistor" ; IEEE Transaction on Electron Devices, july 1976

-E. Braun and S. Mac Donald, op, cit., Chaps. 4 and 5.

[3] -Silicon transistor was well suited to work at higher temperatures than germanium transistor: this difference was essential for military application; germanium transistors failed at about 113 F (45 C)

sequence of product-process inventions made finally possible mass production of standardized and interchangeble transistors; a special role was played by the planar transistor that, being flat, required only the manipulation of one side and was, therefore, perfectly suited to the manufacturing process based on photolithography.

The impact of transistor and, more generally, of semiconductors, has been multiplied by the derived products made possible by miniaturization and integration; their development and diffusion required the design of new transistors (MOS, MOS FET, etc).

4.-Inducement mechanisms[4]

There were strong inducements to try to get a new device performing the essential electronic functions of the vacuum tube but without its inconvenients. The vacuum tube was not reliable; consumed a lot of power and had a short working life and, as a result, needed much space and complementary devices.

Mervin Kelly, the head of Bell Laboratories at that time was perfectly aware of these inconvenients. A team was formed in January 1946 to develop a solid state amplifier; the explicit objective was to replace the vacuum tube.

On the other hand, the electronic industry was already existing: therefore, to get a better device would have had the advantage of an assured market.

The transistor was this new and better device.

Given the radical consequences of a failure of the electronic systems in military applications (weapons guidance, communications, etc.) and also in certain civilian applications (switching systems,

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[4]-I am refering to N. Rosenberg's inducement mechanisms: "Our position, then, is that the ultimate incentives are economic in nature; but economic incentives to reduce cost always exist in business operations, and precisely because such incentives are so difuse and general they don't explain very much in terms of the particular sequence and timing of innovative activity. The trouble with the economic incentives to technical change, as an explanatory variable, is precisely that they are so pervasive... What forces, then, determina the direction in which a firm acutally goes in exploring for new techniques? Since it cannot explore in all directions, what are the factors which induce it to strike out in a particular direction?" N. Rosenberg, Persepectives on

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navigations aids, medical instrumentation, etc.), the search for increasing reliability levels was, and is being, very compulsory at the different developemnt steps; we will have the opportunity to emphasize this point.

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Modern electronics and microelectronics would not exist without the Integrated Circuit, anticipated in 1952 by G.W.A. Drummer: "With the advent of the transistor and the semiconductors generally it seems now possible to envisage electronic equipment in a solid block with no connecting wires. The block may consist of layers of insulating, conducting, rectifying and amplifying materials. The electrical functions being connected directly by cutting out areas of the various layers".[5]

The inducement mechanisms that focused attention on the necessity of proceeding to the integration were twofold:

a) on one hand, the unbalance between the increasing complexity of circuits and the decreasing reliability created by the rising number of wired connections;

b) on the other hand, the search for miniaturization, specially related to the arms and space race.

(cont.) Technology, Cambridge Univ. Press, Cambridge, 1976, pgs .110-111.

[5] -G.W.A. Drummer, Electronic Invention 1975-1976. Pergamon Paen, Oxford-New York, 1977

Wire connections were the main cause of failure: so it was crucial to solve the problems by eliminating solders. The printed circuit had contributed to it but, even when it made possible the suppressions of all interconnections, there still was a crucial problem: the connection of differents components to the network.

Miniaturization was not essential for the most part of civilian applications; on the contrary, it was crucial for the military ones (included those connected with the space race); [6,7]

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[6]-A Rockwell report emphasized:"The systems required to guide and control missiles and aircraft were more intricate than any electronic systems ever devised prior to World War II. The increasing functional complexity of the systems meant that ciruitry to perform the functions had to be increasingly complex and this meant a constant increase in the number of components per system with each functional advance. To keep the system weight down and range and pay load up, electronic components and the systems containing them simply had to decrease in size and weight".

"there was another problem, too, that stemmed from increasing system complexity. This problem had to do with the important consideration of reliability", M.Smith Parks, Microelectronics in the 1970's, Rockwell International, 1974, pg.3.

[7]-For a detailed analysis of the trend of miniaturization in different industries in the early 1960's see H.D. Gilber, ed. Miniaturization, Reinholh Pu. Co. New York, 1961. Even if the book covers medicine, computers, consumer products and other civilian sectors, the editor states clearly that: "There is no doubt that modern miniaturization has recieved its greatest impetus from the national defense program. It has been estimated that anywhere from

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as a proof of this the military were supporting different research programs oriented to the objective of miniaturization; these programs were not successful.[8] The first (germanium) integrated circuit[9] was made in october 1958 by J. Kilby, from Texas Instruments; a few months later, R. Noyce, from Fairchild, solved in a very satisfactory way the problem of connecting the different elements. Noyce's approach would be the dominant in the future.[10]

7(cont.) 50 to 80 per cent of all miniaturization production today is designed either directly or indirectly for defense", pg. 2.

It is also meaningful that, refering to the "Annual Miniaturization Awards competition", the editor wrote: "The most significant fact about entries since the program's inception has been the strikingly discernible trend away from miniaturization of mechanical parts towards miniaturization of electronic parts", pg. 9.

8-The US Navy supported the so-called tinkertoy assembly technique; the Air Force fundes the "molecular electronics" approach. See E. Braun and S. Mac Donald, op, cit, Chap. 6.

9-See:

-J. Kibly, "Invention of the Integrated Circuit", <u>IEEE Transactions on Electron Devices</u>, july 1976.

-Wolff, M. "The genesis of the integrated circuit", <u>The IEEE Spectrum</u> august 1976.

-E. Braun and S. Mac Donald, op. cit. Chap. 8

10-G. W. A. Dummer, in his book <u>Electronic Inventions 1745-1976</u>, Pergamon Press, Oxford-New York, 1977, mentions -in relation with the integrated circuit- his own contribution and also J. Kilby's invention but does not mention Noyce's contribution.

Given the interest of the military for integration and miniaturization it's not a surprise if the defense market[11] was the bugger one. Later, civilian markets developed (hearing aids, radios, etc.)[12].

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It was not obvious that the search for miniaturization would result in a cost reduction trend[13] and, finally, would be the key for the spread of microelectronics.

As a matter of fact, there are two main reasons for this associations:

a) the technical fact that electronics deals with information (and not with material processing); given this specificity, miniaturization reduces power consumption and rises the speed of operation.

b) the development of a specific manufacturing technology, well suited for microproduction: photolithography.

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11-During the years 1962-1966 the defense production as percentage of total production was, respectively: 100, 94, 85, 72 and 53%; see J. E. Tilton, International Diffusion and Technology: The Case of Semiconductors, The Brookings Institution, Washington, D. C., 1971.

12-In 1963 appeared the first comercial utilization of integrated circuits: hearing aids. In computer, the transition to integrated circuits occurred with the IBM System 360 (third generation) also in the sixties.

13-This was not, obviously, the main focus on the military applications.

The increasing complexity of Integrated Circuits implied a rising specificity of their applications reducing, therefore, the corresponding market;[14] as a result costs were high.

The solution to this problem was rooted in a simple but fruitful idea: to build a programmable Central Process Unit (CPU) on one chip, with no wired connections (internal). The programmable CPU was an old and central idea in the computer industry but was a new one in the components industry.

The new device -the microprocessor- implies the possibility of mass production of a flexible element; furthermore, the integration on a chip meant a new jump in reliability. Standardization and reliability were old inducement mechanisms very powerful in the electronic components industry: flexibility was a new one, necessary to maintain standardization and mass production.

A team commanded by M. E. Hoff, jr., from Intel, designed the first 4-bit microprocessor; it was introduced in the market in 1971, as the 4004. One year after Intel introduced the 8-bits microprocessor, (the 8008).[15]

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[14]-In the early 1971 two standardized LSI product had been developed: the first 1-K bit RAM and the first UART (universal Asynchronus Reciever Transmitter).

[15]-Intel was contracted in 1969 by a japanese company (Busicom) to produce integrated circuits for calculators; the chief of the project -M.E. Hoff, jr.- make the crucial choice: to develop a single chip that could be programmed operating like the different integrated circuits necessary for the calculator. This first 4-bit microprocessor was a central process unit on a chip; it was called Intel 4004 and it was introduced in the market in 1971. The 4004 with additional complementary chips was used to

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After this two experiences the idea was well recieved: in 1974 were introduced the Motorola 6800 (8-bits), the National Semiconductor Pace (16-bits), the Rockwell International PPS-8 (8-bits) and the Fairchild F-b (8-bits).[16]

The microprocessor did not imply neither a scientific advance nor any technological leap[17]. It was, basically, the result of a clever

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15(cont).to produce a microcomputer (MCS-4) and was used to control rather simple industrial devices.

The second microprocessor, the 8008, was also manufactured by Intel. Display Terminals Corporation order it to control a cathod tube display: The 8-bit chip results too much slow for the required application; however it was introduced in the market in 1972, even if the team was assigned to other tasks. Nevertheless sales developed and grew. These unforseen results induced Intel to try a new approach. Neither the 4004 nor the 8008 were designed as general purpose devices: the new microprocessor -the 8080, developed in 1973- was the first general purpose microprocessor.

16-See:

-J. G. Giarratano, Foundations of Computer Technology, Howard W. Sams and Co. Indianapolis, 1982, Chap. 2.

-G. Bylinsky, "Here Comes the Second Computer Revolution", in T. Forrester, ed. The Microelectronic Revolution, the MIT Press, Cambridge, Mass, 1981.

17-The two first large markets for microprocessor have been, as it is well known, hand-calculators and digital watches.

design[18], introducing flexibility through the use of programming.[19,20]

[18]-G. Moore wrote with a clear perception: "The advent of the micro-processor as a general-purpose digital electronic block, whose functions are determined by programming, is revolutionary....Design engineers who have previously been concerned with realizing logic systems by wiring together small or medium-scale IC find themselves faced with such a blocks as processors memories and I/O controllers that must be programmed to work...In essence, the previous task of logical inter-connection of gates has been to a large extend usurped by the semiconductor manufacturer and many equipment-design engineers have been forced to consider the system at a higher level with the need for familiarity with the new discipline of programming...In many ways this changes is similar to that which occurred upon the existence of IC". G. Moore, "Microprocessors and Integrated Electronic Technology", Proceedings of the IEEE, june 1976.

[19]-Flexibility through programming is also a main characteristic of modern manipulator robots; however, they also need changes in hands, grippers and/or tools; see J. F. Engelberger, Robotics in Practice, Amacom, A Division of American Management Association, 1980.

[20]-The collective book R.T. Lund et al., Microprocessor applications Cases and Observations, London, HMSO, presents eight cases of applications covering the areas of: a) heating, ventilation and air conditioning; b) automobiles; c) word processing; d)electronic postage scales; e) process control in discret product manufacture; f) medical equipement; g) monitor for Hydraulical cranes; h) sewing machines; One of the concluding observations of the study is the following one: "The motivation for most microprocessor applications is product-performance rather than product-cost", pg. 164

Singer's case is relevant as an example of the difficulties

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20 (cont.) of a precoucious innovator. When designing the first electronic sewing machine, in 1971, they did not find on the market a suitable microprocessor with the required characteristics: so they had to contract a custom designed one to a small manufacturer; without this risky decision Singer would have lost five years of commercial leadership. A. F. Shackill, "Design case history: Singer's electronic sewing machine", IEEE Spectrum, february 1981; see also, R. T. Lund et al., op. cit. Chap. 9.

5.-Manufacturing technology

Photolithography (or photoengraving) -as we have already emphasized, is the specific technology that has made possible miniaturization, and, more generally, the development of microelectronics. Its crucial features are:

a) it is a chemical, not a mechanical, process and so, it is not constrained by the accuracy limits of mechanical manufacturing procedures;[21]

b)it uses the chemical transformations produced by the light so, these ones can be perviously reduced using optical devices, with a high level of accuracy.

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The first step in the manufacturing process[22] is the logical design of the ciruict, followed by the physical design; both processes are computer aided; computers are also used to simulate and test the operation of the circuit.

Once completed the design, the next step is the production of different (enlarged) masks reproducing the geometrical patterns of components and connections. The reduced projection of masks is used to produce the chemical transformations that will reproduce the specific tridimensional pattern on the different die belonging to the same silicon wafer.

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[21] -In note 7 H. D. Gibert emphasized the trend toward increasing electronic miniaturization, contrasting with the opposite trend in mechanical systems.

[22] -See:

-J.G. Giarratano, op. cit. Ch. 6.

-W. G. Oldham, "The fabrication of microelectronic circuits", in Scientific American, <u>Microelectronics</u>, W. H. Freeman, S. Francisco. 1977.

In the most simple case the photoengraving of the microscopic pattern in a silicon wafer covered by a tiny layer of (insulating) oxide proceedes as following:

a) the oxidized wafer is coated with a layer of light sensitive material (photoresist);

b) then it is exposed to ultraviolet light through a mask reproducing the pattern to be engraved;

c)ultraviolet radiation induces insolubility in the photoresist; therefore, when the wafer is immersed in an acid solution, this one attacks the oxide eliminating it;

d) finnally, the photoresists is eliminated by means of another chemical procedure.

The wafers have to be done of highly pure silicon using sophisticated crystal growth techniques; the necessary impurities (dopants) are also added and, finnally, the single cylindrical crystal is cut into thin wafer that are highly polished. Additional impurities have to be added when the wafer is processed.

Once finished the process, the die are cut and tested; finnally they are packed.

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The limits of photolithography accuracy are the limits of optical resolution; therefore, to obtain higher levels of integration, new technologies have been developed based in the same principles but using wavelength shorter; this techniques are based on x-rays or on electron beams.[23]

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[23]-J. G. Giarrantano, op. cit. Ch. 6.

New product design and a specific manufacturing technique have produced a radical transformation in electronics, creating the possibility of cheaper, miniaturized, reproducible and reliable elements: these characteristics are central to the diffusion of microelectronics.

6.-Technological and scientific complementarities: creative unbalances in the manufacturing process.

The development and manufacturing of microelectronic devices requires to control a large variety of procedures, almost all science-based or high-technology-based; so, it requires, for example:

.to control silicon crystal growth minimizing the number of defects;
.to perform controlled diffusion of dopants into crystals and wafers;
.to proceed to the logical design of circuits;
.to design the physical pattern of the circuitry;
.to use efficiently "computer aid design" (CAD) at different steps of the global process;
.to use computers in mask manufacturing and in chip testing;
.to apply classical -or non-classical- photolithography to get the tri-dimensional pattern of the devices.

the result it is not only the need to understand and control these complex and sophisticated procedures but also to coordinate global design and process interaction. On the other hand, this multiplicity of features in the manufacturing process induces potential creative unbalances, in the sense that an advance in one field creates the need for a complementary leap forward in another field, generating thus an inducement to solve a larger problem.

One example of this mechanism is the need for new photoresists connected with the development of new photolithographic processes based on electron beams or on x-rays. Another one is the need for more accurate optical systems to deal with the problems created by the increasing size of wafers.

It might be useful to emphasize the fact that these kind of unbalances are related to the manufacturing processes; on the contrary, those underlined previously, in relation with the transistor the integrated circuit or the microprocessor were connected with product performance.

7.-Technological transfer

As has been emphasized, the utilization of photolithography has been crucial for the development of reproducible and reliable integrated circuits and microprocessors.

The fundamental technique has been developed in the printing industry and its transfer to the semiconductors industry is presented by Braun and Mac Donald as "another example of interdependence of technologies and of cross-fertilization"; this is right but it is necessary to keep in mind that the transfer was not a jump but a progressive movement: photoresists had been used for printed circuits manufacturing and also for chemical milling.[24]

On the contrary, there was an essential continuity between transitor manufacturing and integrated circuits production:[25] procedures of electrical isolation, connection and diffusion were the same.

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[24]-"In 1953 Kodak introduced a photoresist that was designed for the printed circuit and chemical milling industries...With the development of the microelectronics industry came a demand for photoresist capable of adhering to different surfaces and permiting the etching of very fine lines. The second generation of synthetic polyner photoresists was formulated to meet these demandas", R. A. Colclaser, Microelectronics. Processing and device design, J. Wiley, New York, 1980.

[25]-J. Kilby, the inventor of the integrated circuit at Texas Instruments emphasized: "it should be noted that one of the great strength of the integrated circuit concept has already been that it could draw on mainstream efforts of semiconductors industry", J. Kilby, op, cit. pg. 652.

The same continuity existed in the case of the microprocessors; both cases are examples of "direct fertilization" from the own industry; there are reasons to think that direct transfer is easier to assimilate than crossed transfer.

8.-Redistribution of knowledge.

In 1970 Intel began to manufacture semiconductor memories announcing its 1103 random access memory (RAM) chip; the new approach for producing central memories was successful and put the classical magnetic core memories on the deadline.[26]

The existence of semiconductor firms producing microprocessors and/or memories, and also other firms manufacturing different peripherals as printers, disks memories, etc. implied that -specially the first group- they control crucial elements of computers design; they had a knowledge previously monopolized by computer manufacturers. This new distribution of knowledge has had impact on the structure of the industry.

Some big firm, like IBM, decided to make their own chips, to control all the essential knowledge connected with the production of their computers.[27]

On the other hand, the possibility of buying in the market microprocessors, memories and periphericals opened the possibility of new entries in the minicomputers segment and specially in the microcomputers market.[28] In addition, the experience learned by doing microprocessors and memories has induced several firms to move into computers manufacturing.

Finnally, the experience learned by using microprocessors in the production of other devices has been used by certain firms to produce microcomputers, (Attari, Timex, etc.).

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[26]-However IBM personal computer uses Intel 8088 microprocessor.

[27]-Invented in 1951 by J. W. Forrester and his group.

[28]-In a recent catalog of 22 microcomputer, 13 used the Intel microprocessor 8088, 4 the Intel 8088 chip, 4 the Motorola 6800 and one the Z8001; see High Technology, sept.-oct. 1982, pg. 46.

9.-Patterns of cost reduction; technological trajectories

Even if transistor experienced cost reductions, it was with integrated circuits that the trend has become spectacular.

The main patterns in cost reduction are:[29]

a)increasing the quality of silicon crystal and wafers, which implies a reduction in the density of defects and, therefore, a raise in the yield;

b)an increasing size of the silicon wafers. Both a)and b) are related to a better control of crystal growth process. Bigger wafers implies that an increasing number of chips can be simultaneously processed and, as a consequence, fixed costs (design, mask production, etc) are distributed among a greater number of chips;

The yield raises too because, with a given distribution of defects, the proportion of deffective chips is reduced as the size of the wafer increases.

c)increasing complexity of chips, with an increasing number of elements. This approach requires a more powerful power of resolution in the photolithographic process.

d)chip size reduction with given complexity: it reduces power consumption and, specially, increases the speed of operation of the circuits.

These are cost reductions common to a batch of chips. The costs of packing and testing are related to every individual chip and they are, furthermore, labor intensive.

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[29]-See:

-National Academy of Sciences, Science and Technology. A Five year Outlook, W. H. Freeman and Co.

-R. Noyce, in Scientific American, op, cit.

-R. Noyce, "Hardware prospects and limitations", in M. Dertouzos and J. Moses, eds. The Computer Age: the Twnety-Years View, The MIT Press, Cambridge, Mass. 1981.

These patterns of cost reduction[30] have produced neat technological trajectories:[31]

a)-increasing circuit complexity (components by chip) versus time;

b)-decreasing minimum average of the line width (measured in microns) versus time;

c)-decreasing silicon die area (mm^2) versus time.

And these pattern have induced specific learning by doing cost curves:

d)-decreasing logic gate costs (cts. per gate) versus time;

e)-decreasing average price per unit (dollars) versus industry's accumulated production (in millions of units);

f)-decreasing cost per bit of computer memory (cts.) versus time.

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[30]-The dramatic reduction in the cost of microelectronic circuits achieved in the past few years has not resulted from any major break through in fabrication technology. Indeed, most of the basic manufacturing processes involved have been widely adopted in the industry for five years or more", W. G. Oldham, op. cit.

[31]-R. N. Noyce (1977), (1981).

10.-Electronic integrated components

The electronic integrated components we have analyzed -considered from the point of view of hardware- have some common characteristics that conditions their technological development: they are complex-miniaturized-monolithic-information-systems.

Their complex-miniaturized characteristics are obvious. Their monolithic feature arises from their specific manufacturing technology by means of photoengraving. Monolithic microstructures make these systems strongly sensitive to failure (even if they are highly reliable): they are impossible to repair and, given their cost, it is cheaper to substitute the module.[32] On the other hand, cost reduction will make possible to apply redundancy[33]

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[32]-Actually, there are computer with multi-chip processors, so that if one of them fails the rest of the system operates correctly or at a degradated level.

[33]-"Redundancy in some form would allow much higher levels of integration that would otherwise be possible. As circuits become more complex, it appears that the overhead expense for achieving fault-tolerant circuits is a smaller portion of the total. For example, error correction for an 8-bit word requires an additional 4 bits, whereas correction for 64-bits word requires only 7 additional bits. A similar case can probably be made for logic. The relative cost of including redundancy is less in more complex systems. Today, error correction is used in large memory systems to reduce failure rates", R. Noyce, op. cit (1981).

Some big computer already use redundancy, as it is the case of the IBM-370-3033MP, that has several COU, so that if one CPU fails, the system is modified to continue in operation.

The utilization of two computers in paralel is very common (cont.)

principle, duplicating some essential elements.

Their nature as information systems implies that they process energy but only because of its information content: that is the technical reason of their potential miniaturization that, on the other hand, has been possible, in terms of mass production, because it proved to be cost effective with the utilization of the specific manufacturing process.

As we have seen, the development of these systems has been strongly sensitive to the search for increasing reliability levels, because of the consequences of a failure in the most part of civilian and military applications (computers, avionics, medical instrumentation, weapons guidance, etc.).

Miniaturization has also been a modeling force that, even if it has been its own inner logic and its specific features, it has also been connected with reliability. Finnally, flexibility -as we have seen- has been a crucial feature with the rise of microprocessors.

Globally, the driving force in hardware technology innovation has been learning by doing. The experience in production activity. However, if we concentrate in microprocessors, with their flexibility through software (programming) the dominance of "doing" may change. First of all, the trend towards very large scale of integration will reduce still more unitary costs of hardware and, as a consequence, labor-intensive-software-development will be, more and more, the dominant part of total costs. As a matter of fact this is already a trend operating in the computers industry.

(cont.)33 -in real time systems in which the loss of information or a system failure can be a catastrophe.

Programming approach to microprocessors is evolving.

At present, microprocessors have to be, frequently, programed directly in machine language because they do not have enough memory tocontain programs written in Assembler (or in higher level languages): the memory should have to be large enough to contain the compilator (or the interpreter) and the application program.[34]

Therefore, given the fact that writing programs directly in machine code is costly and no reliable, one technique very frequently used is to program a computer using Assembler, to compile the program and, finally, to transfer the machine code to the microprocessor; this special kind of computer is called "development system" and it is a good example of the interaction between computers and microprocessors; the reverse example exists too: at present, not only microcomputers but also minicomputers and mainframes use microprocessors as CPU.[35]

The trend, however, goes in the direction of using high level programming languages, and in this change, algorithms, and programming in the classical sense will be central to the development of systems. "The distinguished feature of both algorithms and programs is that they cannot tolerate the slightest degree of vagueness. In other words, they must so well defined that a mere machine can follow them as written...The difficulty of software, that is, program development, springs directly from this and from the fact that large programs are among the most complex objects that

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[34]-There are exceptions new Trends; so, Microsoft BASIC, for example is contained in a ROM and takes up 8K bytes of memory; PASCAL is also frquently accepted as a high level language for microprocessors.

[35]-Some microprocessors include not only the CPU but also other (cont).

mankind has ever attempted to build".[36]

On the other hand, "unfortunately, today's software is not based on theoretical foundations and practical disciplines that are traditional in the established branches of engineering. No doubt, many of the problems that occur during the software development, acquisition, operation and maintenance cycles are in part symptomatic of this lack of knowledge of the fundamental nature of computer software and its life cycle process".[37]

The final result with microprocessors will, probably, be that "learning by using"[38] will complement learning by doing[39] for the same reasons it is compulsory in the computer industry where "the development of effective software is highly dependent upon user experience..This is so because most of software products admit a wide variation of inputs and processing options. The full range of these options cannot possibly be tested prior to the release of software".

35(cont.)-elements like Memories (RAM and ROM), I/O control elements, etc.; they are called microprocessor systems. There are also multi-chip microprocessors.

36-National Academy of Sciences, Science and Technology. A Five Year Outlook, W. H. Freeman and Co., S. Francisco, 1978, pg. 227.

37-M. Denicoff, "Sophisticated software: The Road to Science and Utopia", in M. Dertouzos and J. Moses, eds. (1981), op. cit., pg. 384.

38-N. Rosenberg, "Learning by Using", Stanford, unpublished.

39-It would be, for example, important to analyze the role played by international organizations of computer uses (SHARE and GUIDE for IBM users).

Software will be dominant,[40] not only in cost terms but also in learning requirements.

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[40] -Reading the annual Review of the IEEE Spectrum, it is evident the increasing importance of software problems, both for computers and microprocessors:

"The software crisis is, in a nutshell, the excessive cost of designing and updating software and the growing distrust of users with software because of the frequently poor quality of delivered programs, specially at large-scale installations", R. Bernhard, "Computers: emphasis on software", IEEE Spectrum, january 1982, pg. 32

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Introducció:

L'objectiu del curs és presentar una visió global de les característiques, condicionants i conseqüències del canvi tecnològic, i en especial, de les seves relacions amb el desenvolupament econòmic; el curs inclou una anàlisi en profunditat dels processos d'invenció, innovació i difusió. S'estudiarán de forma detallada quatre monografíes (microelectrònica, enginyeria de disseny i d'execució, software i producció d'acer mitjançant injecció d'oxígen) així com s'explorarán el problemes de les polítiques científiques i d'innovació i l'estat de la problemàtica a España i a Catalunya.

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