Evolution of Computers and Computing

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The evolution of computing and computers is particularly attractive to depict since most adults of today have lived through it in its entirety. Computers, as I will be describing them, have just (in 1976) celebrated their formal 25th anniversary. As 25-year-old computing devices, electronic, digital, stored program computers are very young.

Indeed, any comprehensive chronology of computers (*1*) would always trace the origin of computing devices to the counting table around 400 B.C. and the abacus used in China as early as 500 B.C. In such a chronology, the history that is identified with the type of computers we are treating is the history of machines which (i) perform calculations with numbers, (ii) manipulate or process data (information), and (iii) control continuous processes or discrete devices—often called manipulators—in real time or pseudo real time.

Within this rather broad definition, some of the key characteristics which are epitomized by the young breed of electronic, digital, stored program computers are:

1) *Their digital operation*, which has placed great emphasis in mathematics on discrete computation methods and the use of discrete structures in the solving of mathematical and logical problems. This digital feature has such overwhelming advantages (*2*) that a strong trend toward total digitalization has occurred in equipment, especially where functions were previously implemented by electromechanical or analog devices.

The digital feature—often considered a limitation—of the computer has necessitated the conversion to discrete form of the previously more common continuous world of curves, surfaces, and functional relationships with which mathematicians, physical and biological scientists, and economists were most familiar. As Birkhoff so aptly put it (*3*), "computers seem to have restored a balance in mathematics. Newton and Leibniz along with the Calculus emphasized and focused attention on continuous functions and theories of convergence and limits. Computers spun attention around to discrete mathematics. Combinatorics, heuristics and number theory were exemplary of the fields of mathematics that have flourished since the advent of computers."

The computer's digital nature was due in turn to the nature of electrical circuits circa the 1940's when the most common form of storage of numbers (data) were the flip-flop, the electromechanical relay, and the gas tube. These devices which could "exist" in one of the two states led to the need for binary representation of numbers. The rest is history. We have become accustomed not only to binary representations of digital numbers and alphabetic characters, but we now are quite comfortable with curves, graphics, and pictures formed by binary means, that is, through the placement of dots (or spots of light).

The many advances in electronic and optical technology have not changed our reliance on digital operation or discrete representations of relationships and computation methods. The large-scale integrated (LSI) circuits of 1976, which contain on chips less than 1-inch square, the equivalent logic found in 1956 in a room full of vacuum tube circuitry, are still dependent on being able to distinguish between one of two electronic states and thus on binary operation.

2) *Their stored program capability*, probably the most distinctive feature of the new computer of the 1950's and the single characteristic which has led to the so-called "Second Industrial Revolution," or the computer revolution of the latter half of the 20th century. This idea—an insight of genius—was that of John von Neumann. He conceived and described in the 1940's the notion that the instructions for the computer be written in the same form as the data being used by the computer; then, instructions could be operated on just as could numbers; this allowed instructions to be modified and different sets of instructions to be selected based on intermediate results derived by the computer with no human intervention. This idea as expressed in its initial conceptual stages is interesting. In 1946 we find von Neumann, Burks, and Goldstine writing (*4*, p. 1):

> . . . *the machine must be capable of storing* in some manner not only the digital information needed in a given computation . . . and also the intermediate results of the computation . . . but also *the instructions which govern the actual routine to be performed* on the numerical data. In a special-purpose machine these instructions are an integral part of the device and constitute a part of its design structure. *For an all-purpose machine it must be possible to instruct the device to carry out any whatsoever computation that can be formulated in numerical terms* [italics mine].

Coincident with the concept of the stored program was that of the computer itself being able to select and vary the sequence of instructions carried out. Again, this remarkable conception was due to von Neumann and in early writings (*4*, p. 3) was described as follows:

> The utility of an automatic computer lies in the possibility of using a given sequence of instructions repeatedly, the number of times it is iterated being either preassigned or dependent upon the results of the computation. When the iteration is completed, a different sequence of orders is to be followed, so we must, in most cases, give two parallel trains of orders preceded by an instruction as to which routine is to be followed. . . . Consequently, we introduce an order (the conditional transfer order) which will, . . . cause the proper one of two routines to be executed.

Thus, the truly innovative concept of the stored program is dependent on the realization of conditional transfers and indexing internal to the computer and free from the need for human intervention.

3) *Their self-regulatory or self-controlling capability* (*5*) which is based on repeated sequences of prediction, performance, observation and measurement of the difference between actual and desired result, and modification allowed purposeful behavior to be engineered in hardware. This capability, incorporating, as it did, the concept of feedback led to computers probably being the first "goal-seeking" machines and the first robot devices. It is apparent that the capability for self-controlling or self-regulating is dependent on automatic modifiable stored programs (see point 2 above).

4) *Their automatic operation*. Although this capability may be derivative from the computer's modifiable stored

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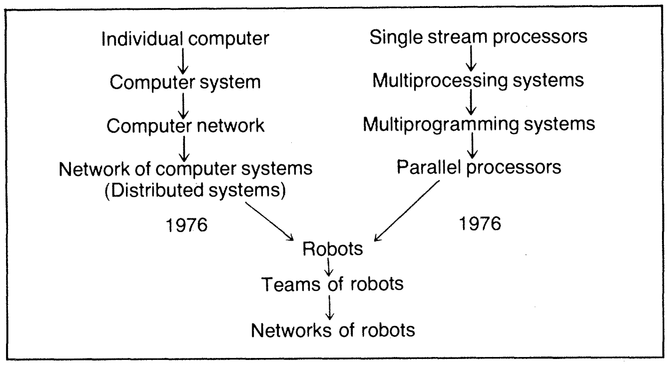

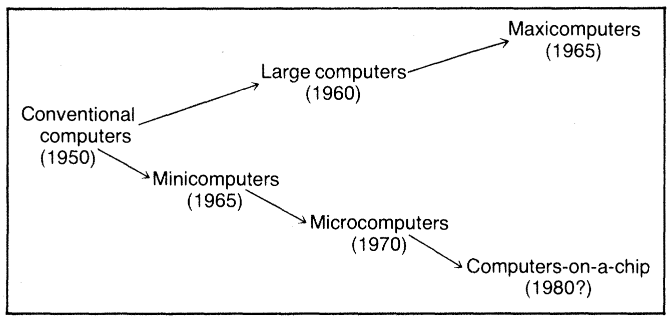

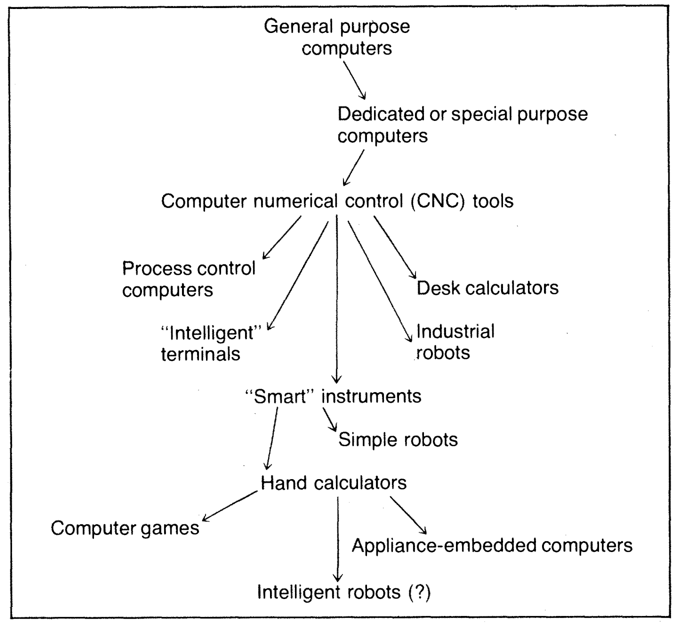

Fig. 1 (top left). Engineering developments highlighting complexity of interconnection or function. Fig. 2 (bottom left). Engineering developments highlighting the size of computers. Dates in parentheses approximate the year in which the particular computer type was first commercially available. Fig. 3 (right). Engineering developments highlighting the packaging of computers for end-use or for application (in approximate chronological order).

program and self-regulatory features, it deserves separate identification. The capability of automatic operation, which implies that the computer operates independently of human operators and human intervention after its computations start, is essential to the early visions and theories of von Neumann, Norbert Wiener, Claude Shannon, and Alan Turing. It is also the basis for the more sophisticated applications of computers in space, nuclear energy, weapons delivery systems, process control, cryptography, and robotics.

5) *Their reliance on electronics*. This is perhaps the most time-dependent feature of computers and it may be a significant trait only for the first 25 years of history. And yet the use of electronic devices (*6*), in which the movement of electrons could be controlled, provided for the first time in the 1940's and 1950's the reliability and speed of operation, the practical size, and the automatic operation that made the computer as we know it today possible. Electromechanical relays, hand-wired plugboards, and manually set switches, as opposed to electronic circuitry, simply would not have provided an adequate engineering basis for computer development.

By the 1970's however, electronics had been joined by optics, by crystallography, by plasma physics, and even by polymer chemistry in providing the components for computers. Indeed, the need for materials and packaging brings with it all kinds of complex problems of material processing and material choice in semiconductor devices. Also, surface physics and chemistry are becoming of extreme importance as miniaturization, plasma etching, and superconductivity become part of the computer design process (*7*).

In summary, then, the principal traits of computers which have been reflected in their evolution to date and which hold the key to immediate desired advances are (i) their digital operation, (ii) their stored program capability, (iii) their self-regulatory or self-controlling capability, (iv), their automatic operation, and (v) their reliance on electronics.

Environment Generated by Computer Engineering Developments

Engineering developments since 1950 have not converged to yield a specific instrument that typifies a computer. One might expect that this would have occurred on the basis of historical precedents such as the automobile, the airplane, the microscope, the television set, and the like. However, in the computer field, engineering and architectural advances coupled with almost revolutionary changes in mathematics and logic have actually resulted in a divergence in what might be considered a computer.

There are several pragmatically distinct lines of engineering development which display the rapidly changing computer environment of the last 25 years. They can be pictured in terms of (i) complexity of interconnection and function, (ii) size of computer device (or system), and (iii) packaging for end-use or for application.

Graphically, these developments are shown in Figs. 1 to 3, where each listed entry represents a physical manifestation of a computer, a group of computers, or a self-contained computer-controlled device.

In Fig. 1 (*8*), *single-stream processors* are confined to the sequential or consecutive execution of program instruction streams; *multiprocessing systems* are systems that will simultaneously execute two or more computer programs; *multiprogramming systems* are systems that provide for the interleaved execution of two or more computer programs by a single central computer; *parallel processors* allow for the simultaneous execution of two or more process streams in a single unit; and *robots* are defined as devices that have computerized motor control, computer-controlled sensor abilities, and some features of human intelligence, and that interact directly with their physical surroundings.

In addition, it is important to note that (*9*),

> A computer network, in the broad sense, is any system including both data processing equipment and data communications equipment. . . . The data processing equipment

may consist of some number of computers or a variety of different terminals, supplied and maintained by the users of the network. The communications equipment may include a mix of equipment such as circuits, modems, multiplexors, and concentrators.

Unfortunately, technology has been changing so fast that frequently the definitions of the computer types in Fig. 2 are in terms of cost rather than of engineering characteristics. However, they are still useful in understanding the changing computer environment. The phrases in Fig. 2 have become so commonplace in everyone's vocabulary that it is worthwhile to remind ourselves what they refer to. In this regard the following definitions hold (*10*).

▶ *Minicomputers* are a "class of stored-program digital computers suitable for general-purpose applications and are priced below $50,000 in their minimum configurations." A typical minicomputer is a parallel, binary processor with a 16-bit word length, weighing less than 50 pounds, consuming less than 500 watts of standard 115-volt electric power, and requiring no special air-conditioning.

▶ A *microprocessor* is the central unit of a microcomputer. It is not the entire computer, but it contains the logical elements for manipulating data and performing arithmetic or logical operations on it. To make a complete computer, the microprocessor must be augmented through several support elements such as memory, input/output (I/O) circuits, and other specialized functions.

▶ A *microcomputer* contains at least one microprocessor plus other supporting circuitry, such as I/O interfaces, DMA (direct memory access) logic, interrupt circuitry, memory, and real-time clocks.

▶ A *computer-on-a-chip* is perhaps best described by noting that (*11*) by the early 1980's, it should be possible to visualize the existence of a complete minicomputer system chip less than an inch on a side including a 16-bit central processor unit, 32 kilobits of memory, and simple I/O interfaces. Speed, as limited by power consumption and serialized I/O, might be in the range of 10^5 to 10^6 instructions, and manufacturing costs should be $10 or less.

Most of the names in Fig. 3 have by now also become part of everyday jargon. For example, process control computers are usually thought of as computers controlling continuous manufacturing processes, such as chemical processing, as opposed to discrete manufacturing; "intelligent" terminals are office—or home-size—terminals used to interconnect with computer networks and which contain sufficient logical circuitry to perform like a computer in a freestanding mode; simple robots are exemplified by the Viking lander robot and the lunar robots of the U.S.S.R.; computer games have appeared in the last 3 years in the commercial market, with the most well known being that which uses the home television screen as an electronic display device and contains the controls needed for playing games similar to ping-pong, handball, racquet ball, or squash. Appliance-embedded computers refer to the very recent phenomenon of utilizing inexpensive, miniaturized logic chips to provide computer control of familiar appliances. Recent highly publicized examples are the widely advertised microwave ovens of 1976 controlled by microprocessors. Finally, intelligent robots, possessing some features of human intelligence and being able to perform some functions previously found solely in the domain of people, are close enough at hand to have incited preventive actions.

From these figures, observations and trends which bear both on the evolution of computers and of computing can be extracted. Some fall most naturally under topics appearing subsequently: a few can best be made here.

1) A dominant trend has been the decrease in size and cost of computers (for example, minicomputers, microcomputers, and computers-on-a-chip), which places tremendous computing power within the reach of individuals. At present, this wealth of individual computer assets is exemplified by hand calculators, ranging in price from $10 to $400, and microprocessor kits typically in the price range of $50 to $500. This availability to individuals of computer power under their own control is already exhibiting real potential for dramatic change in the providing of education; in the marketplace for engineering services; in the type and use of home appliances which will in turn affect the role of homemakers; in the provision of health care and in the possibilities for really effective self-practiced preventive medicine.

2) The increasing attractiveness of computer networks has placed almost unlimited computer power in the hands of groups and organizations no matter how small, and in the hands of individuals. The initial price is that of an inexpensive terminal and the telephone lines by which it is connected to computer power "for sale" literally anywhere in the world. The sale price of this computer power is generally based on the computer time and number of computer components used and can, of course, be extremely expensive. But the means are in place through computer networks. Some of the more striking attributes of computer networks include (*12*): (i) The sharing, nationally and internationally, of expensive information resources, scientific computational resources, and computer equipment. (ii) The possibly best means of providing equality of access to and an equality of quality in public services, independent of geographical location. Primary examples are those of health care in remote areas, educational services, particularly continuing education, and public protection through law enforcement networks. (iii) The centralized management, in a real-time sense, of geographically dispersed organizations, whether they be governments, multinational corporations, worldwide weather services, or worldwide monitoring services protecting against natural or man-made catastrophes. (iv) The "perhaps" only means for resurrection of the entrepreneurial environment on which so much of our national industrial and scientific creativity and innovation depends, and which itself depends in turn on the availability to the entrepreneur of the most current information and most modern computational (research) assets.

3) The availability of maxicomputers with sophisticated parallel processing capabilities and complex interconnectivity of components has provided an unprecedented enormity of scientific, statistical, economic, and engineering calculation power. Calculations, projects, and problem solutions totally beyond human attainment which have and are occurring through the use of computers include long- and short-term weather forecasting with useful accuracy, nuclear reactor design and control, economic modeling, modeling of socioeconomic systems for policy purposes (*13*), control of weapons delivery systems, the U.S. manned space program, environmental monitoring, the direct-distance-dialing system of AT&T, and cryptographic applications.

4) The rise of the "computer hobby shop" will probably provide the strongest force to date for developing a first generation of individuals who feel comfortable with computers, who are not afraid of them, and who will exercise in the computer arena that famous American "basement creativity" that has boded so well for us as a nation in the past. The computer hobby shop is not a new phenomenon for those of us who were at least of teen age at the end of World War

II. In the early to mid-1950's, military electronic surplus stores sprang up in cities like toadstools. Some stores even sold surplus or secondhand electronic components by weight.

From this superb collection of electronics—the product of hundreds of millions of dollars of government and industry R & D—amateurs learned to build oscilloscopes, electronic repair equipment, and amazing electronic gadgets. The electronics surplus stores in the 1950's bred the generation of engineers that was able to conceive and advance the computer technologies, the TV technologies, the satellite technologies, and the space technologies of the 1950's, 1960's, and the 1970's.

The computer hobby shop of the 1970's and probably the 1980's is today's counterpart of that older electronics surplus store. In these stores, you can buy teletype machines, modems, acoustic couplers, older versions of electronic display screens, adder circuits, bits and pieces of computers, and all kinds of microprocessors and large-scale integrated chips.

The computer hobbyist of today is any age—from teen-ager to retiree. But for what new science, technology, or engineering fields this new hobbyist will be the pioneer, we do not know for sure. However, I am willing to venture a few conjectures; namely, that our near-term automation and electronics future will see computer control systems in most of our home appliances, our automobiles, and our personal work-easing contrivances such as lawn mowers and powerboats.

A fair prediction for the future based on trends in computer engineering is that there will be a heavy emphasis on computer control of continuous and discrete processes and of real and near real-time processes. This computer control "boom" will result both in substitution of computer control for traditional control systems (as is already occurring in automobiles) and in the invention of entirely new processes not previously possible without computer control. Anticipated instances here include those of useful working robots and of extraterrestrial explorations and colonization.

Quantification of the Evolution of Computers

One of the surprises in reviewing the evolution of computers is the grasp one obtains of the advances, uses, problems, and impacts of computers and computing by noting where computers are and who has been using them. For that reason, some historical and current data are displayed and assessed below.

In the early 1950's, almost all computers were owned by or devoted to applications of the federal government. For example, the first two electronic, digital, stored program computers were ordered by the government to handle the 1950 census. In rapid succession, computers were ordered by the government for weapons calculation, weapons delivery and control, cryptographic applications, nuclear reactor design, nuclear engineering, and inventory and logistical applications.

The computers of 1950 were not devices. They were rooms—big rooms—full of tubes, circuits, ventilating equipment, and people. I might add that the people carrying tapes, pushing buttons, and lowering the room temperature in these old monstrous computers were just as important a computer component as were the tubes and the circuits.

In the mid-1950's, there were fewer than 1000 computers in the United States, and they were all conventional computers with continuously increasing power. There were fewer than 100,000 computer professionals, and about 100 technical leaders in the field in the late 1950's, most of whom knew each other well. In the mid 1960's, there were about 30,000 computers—still conventional big computers. We knew where they were and what they were doing.

At the end of 1976, instead of 1000 conventional computers in the United States, we had some 220,000 computers, about 40 percent being medium or large computers and 60 percent being minicomputers. Minicomputers (minis) are small in size and by definition cost less than $50,000. Most cost less than $20,000. A lot of them cost less than $10,000. As the number of computers increased from 1000 to 220,000 in 20 years, and the number of computer professionals—analysts, designers, programmers, and operators—increased from about 100,000 to about 2,500,000, the number of actual users became impossible to count—especially as most computers became part of computer networks. An easy calculation tells us that, with 220,000 computers in the United States and about 220 million people in the United States, there is now one computer for every 1000 people or one computer for every 240 families (54 million families in 1975). That is about one computer for every good-size high-rise apartment building or every 240 houses.

And we have not yet mentioned microprocessors or microcomputers. As the number of minicomputers and conventional computers increased from 30,000 to 220,000 in the 10 years from the mid-1960's to the mid-1970's, the number of microprocessors increased from none to three-quarters of a million.

By 1980 the number of minicomputers will reach about that number (750,000) but the number of microprocessors will be more than 10 million. They are and will be so small—in the range of inches on a side—and so inexpensive—$10 to $500—for central processing units and logical units that it will be more practical to buy a number of them than to test a single one for reliability.

As minicomputers became a marketable product, we saw the customers or users change from large institutions to small institutions and wealthy individuals. With microprocessors, the customers are potentially everyone.

In addition, it is estimated (*14*) that some 30 percent of the computers in the United States are parts of computer networks (that is, they use an average of 20 terminals) and that (*15*) some 34 percent of federal computers are part of networks.

These statistics and data are useful in that they make it apparent that we can no longer know who is using computers and what they are computing. Indeed, when anyone with a telephone and between $25 to $50 per month or $2 to $5 per hour can rent a computer terminal and have access to a computer, the number of users is realistically indeterminate.

Other significant information is directed toward finding out who is using computers. As was mentioned above, the federal government was the principal owner and user of computers during the 1950's. That picture has now changed dramatically, as can be seen in Table 1, which shows the ownership within the United States in 1976 of conventional general-purpose computers (not mini- or microcomputers). We can surmise that the future evolution of computers and computing will be markedly influenced by this new mix of ownership, just as the initial phases of development were so strongly influenced by the federal government.

Programming and Software Development

It is very dangerous to venture an opinion that there is "something new under the sun." However, I would conjecture that programming, software, and flow-charting were essentially new concepts tied entirely to the advent of computers. It actually appears possible to assign 1946 as the year the flow chart (or flow diagram, as it was called then) was "invented" by Goldstine and von Neumann (*16*). Even then, the inventors correctly perceived the flow chart as a "logically complete and precise notation for expressing a mathematical problem" which evolved as a "geometrical drawing to indicate . . . the iterative nature of an induction." As a still essential element of programming, Goldstine's statement (*16*, pp. 266–268) of 1946 which comments that the purpose of the flow chart is to give a picture of what is going on in the control process of the computer as it solves a problem, to show the states of variables at key points in the course of the computation and to indicate the formulas being evaluated, is still valid.

In the same manner, 1947 can be assigned as the date for the invention of the computer program as we know it today. Since 1947, programming has not changed in its basics. The term "software" has been coined to include all the programs needed to operate the computer, to perform a given application, and to allow individuals to communicate with the computer.

During the period from 1947 to the present, software or computer programs have evolved into a number of separable product lines differing in purpose and in market availability. Also, as might be expected, a software engineering language or jargon has evolved which has become part of the language of computer science and engineering. About 1968, the phrase "software engineering" itself was adopted (*17*) to describe activities such as programming methodology, software development, programming tools, and programming standards. It is still a young, diverse, disorderly, and expanding field. It is possible, nevertheless, to pictorially show the principal generic product lines into which software has been fitted (Fig. 4).

As one proceeds from left to right in Fig. 4, the software product lines become less dependent on or allied to particular computers and more oriented toward user needs. Programming languages, for example, have been developing primarily since the late 1950's to simulate as closely as possible the natural languages which people use. They employ English words and well-known mathematical symbols as much as possible.

Programming languages are probably the most significant development in the history of software. They allow anyone with just a minimum of training to write or to use computer programs. As a result, they have made computers a universal resource rather than just a device for scientists and engineers.

Table 1. Ownership (by percentage) of general-purpose conventional computers within the United States, 1976 (14)

Ownership by industrial classification	Percent of computers
Manufacturing industry	31.0
Electric machinery—3.5%	
Nonelectric machinery—4.5%	
Other process manufacturing—9.7%	
Other manufacturing—11%	
Transportation equipment—2.3%	
Miscellaneous business	13.3
Advertising, employment, equipment, rental, engineering services, other professional services)	
Banking, credit, insurance, real estate, and other financial institutions	
Trade (wholesale and retail)	13.1
Educational institutions (schools, universities, libraries)	5.7
State and local government	5.7
Federal government	3.4
Transportation carriers	2.9
Medical and health services	2.7
Printing and publishing	2.4
Communications	1.9
Utilities (electric, gas, and sanitary services)	1.6
Other professional services	1.9
Petrochemical industry	1.0

By 1976, it was estimated that at least 85 percent of computer users were working with programming languages. The better known are COBOL, FORTRAN, BASIC, ALGOL, PL/I, and APT.

The first 25-year history of software has not been marked with the successes, the advances, or the decreasing costs associated with computer equipment or hardware. Software or computer programs have evolved from the fields of mathematics and logic; programs are essentially algorithms stated for computer solution, and the correctness of computer programs is based on methods of proof for algorithm correctness.

Listeners always evince genuine surprise when they are told that, today in 1977, there is no theoretical (or mathematically rigorous) way to prove programs correct (except for trivial programs containing less than 100 statements). This serious limitation will be difficult to overcome because of the mathematical difficulty of constructing the necessary inductive assertions and the cost of the computer time to generate the proofs (*18*). The impracticality of exhaustive testing of all program input values can be shown by observing that it would take the "fastest" machine available today more than 30,000 years to try all inputs to a simple multiplication program.

The lack of theoretical proof of correctness of computer programs has resulted in the expenditure of considerable intellectual and physical resources in the software field to develop engineering and statistical substitutes. Software engineers and computer scientists have concentrated on quality-control techniques for software development, "debugging aids," automatic programming techniques, software validation, and the like, but to little avail. Software correctness still remains the most elusive goal of computer science.

As a result, software is the most unsafe, the least understood, and the most expensive component of total computer system costs. Software development costs are now almost 90 percent of total computer system costs. This percentage will probably increase along with the absolute costs of software, since software design, development, and testing is the most highly labor-intensive component of computer system products. The really useful and exciting advances in computing will probably only proceed at the same pace as advances in software engineering. And, this will be distressingly slow.

Computing and Applications

As was mentioned in an earlier section, the evolution of computers exhibited three distinguishable generic lines of computing or application: (i) scientific calculations, (ii) data processing or information handling, and (iii) the control of continuous processes or discrete devices—often called manipulators or effectors.

This distinction is used simply for clarity in describing applications and in highlighting the involvement of different scientific disciplines and customer groups. It is not intended as a means of delineating or defining the market. For, in the current antitrust suit of United States versus IBM, great weight has been given to defining the market and to determining whether there is indeed a useful distinction to be made in that sense between scientific computer applications and data processing applications.

For our purposes in viewing the evolution of computing, it is helpful to observe the following.

Scientific calculation applications are characterized by relatively small amounts of input and output and large amounts of data computation which is often complex in nature. Scientific users have customarily demanded high calculating speeds, high performance, and great computer power. They have not traditionally placed much of a demand on sophisticated applications software because they have the scientific ability to produce their own software (*19*), especially as they gain experience with programming languages. The demands for scientific calculation projects have provided the principal motivation for the development of large, maxi-, and supercomputers. Von Neumann's interests were primarily in scientific calculations using computers, and he can appropriately be considered its first inventive leader.

Data processing applications are characterized by large amounts of input and output and relatively small amounts of data computation. Historically (*19*), data processing users have had lesser capability to develop their own computing applications and have relied more on vendors to provide to them a total computer system including the equipment, software, and continuing support services. They are, as a result, almost completely dependent on programming languages and on the availability in the marketplace of completed application program packages.

The better-known types of data processing application packages include Data Base Management Systems (DBMS) and Management Information Systems (MIS). Other familiar application packages include account billing systems, payroll systems, and inventory control systems.

The initial thrust for data processing applications probably was due to marketplace forces rather than to user demand. At least two computer systems manufacturers, IBM and Burroughs, entered the computer field as a transition from the electric accounting machine (EAM) market. It was natural to simply transfer customers' familiar data processing applications from EAM equipment to computers with relatively little regard for any of the distinctively useful features of computers. This historical occurrence appears to have indeed set the stage for the first 25 years in the evolution of data processing applications.

Computer control applications are less familiar and probably less understood than the other two generic application product lines. In a way, this is surprising since the well-known scientist Norbert Wiener and his scientific child "cybernetics" are so closely associated with automatic control systems (*20*). Computer control applications are characterized by computer control of the state of a continuous process or of the movement and position of a device in accordance with input signals descriptive of the environment of the process or device.

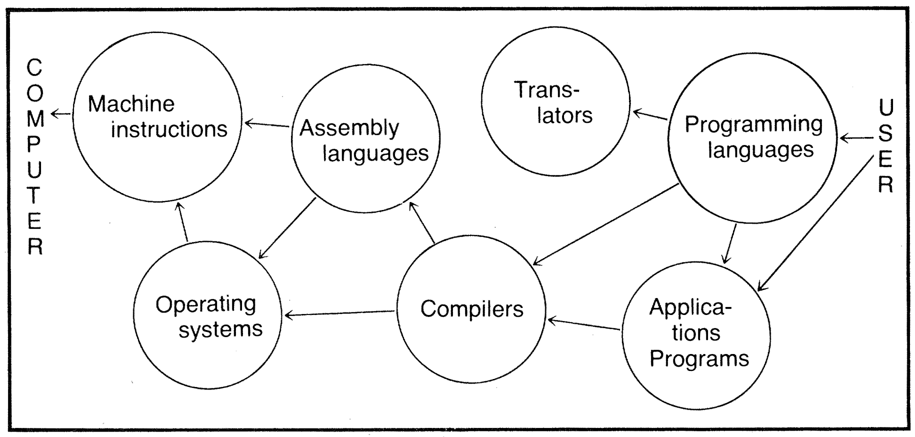

Fig. 4. Generic software product lines.

Applications of this type are newer and fewer than those for scientific calculation or data processing. Examples of process control include computer controlled chemical processes, power plants, and surface mass transit systems (such as BART in San Francisco). Even more scarce are examples of devices controlled by computers. We can cite as familiar instances the Viking lander (*21*), the lunar rover, and numerical control tools.

Computer control applications highlight the importance of the self-regulatory and self-controlling capabilities of computers. Software developments are also fewer in this application area. However, there is a growing consensus that this area may be the fastest growing in the near future.

Concluding Comments

In spite of its relative youth in the history of science and technology, the computer has exerted a powerful and complex influence on our lives. In return, society and the individual, through their visions and concerns, have applied strong and widely varying pressure on computer developments and applications. Where the human has encountered the computer, there has been a play of forces and fears not yet understood or measured sufficiently to foretell the future. But a future for both computer and man, there will surely be.

A profound admiration of and concern in computers by people is to be expected. Computers are properly cited as the first as well as the most important invention ever that significantly extends man's intellectual capabilities. Until the age of computers, inventions had primarily extended our muscular powers as well as certain of our sensory powers. The Industrial Revolution always comes to mind as the epitome of those inventions which replaced or extended man's muscular power. Telephones and microscopes are excellent examples of extensions of our vocal and visual powers.

But throughout all history man was never threatened by anything—animate or inanimate—that could equal, extend, or surpass his intellectual capabilities, until the computer. Now in the last 25 to 30 years, there has cascaded down upon us in an electronic jumble, big computers, supercomputers, "smart" terminals, industrial robots, minicomputers, microcomputers, computers-on-a-chip, teleoperators, and real robots almost like those of science fiction.

We have seen, in this article, some of the history, the trends, the users, and the problems that have coalesced to produce the computer world of 1976. My belief based on the experience of us all is that the balance of power and the ratio of intelligence between man and computer is still indeterminate (*21*). Further, it is not entirely under man's control. In particular, as computers increase their capacities to perform more of the tasks formerly considered only within man's intellectual province, man must have and finally has, the opportunity to equip himself for other functions and a superior existence, or else his survival will seem less important to himself, leading quite unnecessarily to a physical and intellectual ennui.

One way to contemplate the future which does not preempt our choices and which simultaneously puts the computer-man relationship in better perspective is to view the future in terms of four possible scenarios: (i) man without computer, (ii) man with computer, (iii) computers without man, and (iv) computers against man.

Within the setting of these scenarios, what we know about the evolution of computers to date leads me to predict that:

1) Progress, or changes, in the advanced, imaginative uses of computers will be despairingly slow—certainly much slower than in the first 25 years of computer development.

2) The decreasing costs and decreasing size of computers and logical devices will put these scientific artifacts into the hands of large numbers of individuals. We will see spurts of that "basement creativity" for which Americans are so renowned. Computer-related advances will be many, random, and beneficial. However, because of constraints to progress, these advances will be localized without large-scale diffusion.

3) Man coupled with computers will outlast man without computers. This surmise appears reasonable for both individuals and groups in society.

4) Man will continue to increase the number of "intelligent" tasks for computers faster than he does for himself. This paradoxical situation prevails because (i) we like to coax the utmost out of our most fascinating invention; (ii) we are intellectually lazy; and (iii) many people already feel insecure without the computer and are, in short, productively addicted to it.

5) Computers will provide to the individual more control over his personal environment than he has ever before been able to exercise. This capability will result from the miniaturization of computer components along with the decreased cost of computer hardware. Controls now possible range from individual self-paced instruction to the monitoring in real time of vital health signs, to surveillance for public protection of dangerous surroundings such as alleys and hallways. Attainment of these kinds of individual control will be accomplished principally through local ingenuity.

6) Major efforts will be directed toward the use of computers for increasing public accountability. This will take the form of more computers used for more record-keeping tasks.

7) In spite of all man-made constraints, there will be an irreversible but slow trek to realize with computers, forms of intelligent behavior that are essentially limitless, transcending man and computer taken separately.

I feel quite sanguine that people will not, as is so frequently stated, become the victim rather than the master of computers. Further, we are all most fortunate to be part of the process that will be making monumentally important decisions about man's intellectual future.

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Large-Scale Integration: What Is Yet to Come?

Robert N. Noyce

A single large-scale integrated circuit in 1977 can contain more active elements than the most complex electronic equipment ever built 25 years ago. Enormous advances have been made in the last two decades, and we may ask whether this technology is reaching a limit or whether it will continue to advance at a breathtaking pace. By their nature, integrated circuits are small and are limited in power dissipation. As a result, their primary use is in information manipulation, not in areas where high power is required, such as in transmission or in servo drivers. However, a scanning of the titles of this issue shows that information-handling or computerlike devices are central to electronics today. Thus, large-scale integration can have a major influence on the direction of electronics in the future.

The most obvious effect of the development of integrated circuits has been to reduce the size of electronic equipment. However, the principal advantages that have accrued lie in the reduction of cost and in the improvements in performance, reproducibility, maintainability, and reliability.

Interconnections Are the Problem

Interconnections have been, and are, the major problem in computer hardware. Because of the physical size of these interconnections, delays are incurred in transmitting signals from origin to destination with the computer. Because of the capacitance of the interconnections, a power loss is incurred every time a signal is imposed on the

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