Environment and Planning B: Planning and Design, 1986, pages 377-384

The changing technologies underlying computer-aided design

B R Gaines, M L G Shaw
Department of Computer Science, University of Calgary, Alberta, Canada T2N 1N4
Received 25 April 1985

Abstract. Computing is coming to play an increasing role in the design process. However, the role of computer-aided design cannot be understood without taking into account the major quantitative and qualitative changes that occur regularly as generations of computers develop. Computing technology may be viewed as autonomously impacting society. However, it may also be viewed as a product of society, created through its needs and moulded by its values. From this second point of view, the development of computing may be modeled as a succession of social learning processes arising out of the need to cope with an increasingly complex world. This gives rise to successive generations of computers with qualitatively different capabilities. Only now in the fifth generation and beyond are computing systems becoming able to interact with people at the levels of the higher processes of the mind. Thus, their major impact on design is yet to come.

Design and computing

The classical debating topic in design departments over coffee on a wet day is "What is design?" "What is it to do design?" "What is it to teach design?" *Design* is one of those words that everyone uses quite confidently until they have to agree its essence with someone else. Design involves *analysis*. The designer has to be able to understand what is being designed. However, design is not analysis alone. Design involves *action*. The designer has to generate a producible design which can come into existence in the world. Design involves *goal definition*. The designer has to be able to define the requirements. Design involves *creation*. The designer may have to generate something new. In a world of changing requirements and constant innovation in techniques, it is inevitable that most designs are new, and hence acts of creation.

Into this world has entered the electronic digital computer as a new tool aiding design, but one that goes far beyond any previous tool in its capabilities to interact with, and support, the higher level processes of the designer (Gaines and Shaw, 1984b). Designers use many tools to aid the process of design. Some tools are mechanical aids to the designers. Other 'tools' are people in subordinate roles taking on particular design tasks. It is difficult to place the computer within the spectrum of tools. In some applications it appears as a superior mechanical aid, a very accurate multidimensional slide rule. In others it takes on the role of a subordinate person, a draftsman or quantity surveyor. In some of the more speculative design applications the computer appears to be taking a nonsubordinate role and becoming a partner in the creative act.

What is the role of the computer in design? In this paper we argue that it cannot be understood until one realises that computing itself is a product of a rapidly changing society, and that computing undergoes revolutionary changes about every eight years. We have already been through five generations of computing, each differing from the others in major quantitative and qualitative features. It is this that has led to the diversity of roles of 'computers' in design. Projecting this pattern of change into the future gives some indication of the trends in computing, and hence in computer-aided design (CAD).

Computing as a social product

Many writers have speculated upon the impact of computers on our society (Wiener, 1950; Bell, 1973; Mowshowitz, 1976; Weizenbaum, 1976). The impact is now being felt, and many commentators are attempting to analyse its nature and project its trends (Toffler, 1980; Dizard, 1982; Brod, 1984; Turkle, 1984). However, the majority of such speculation and analysis offers one-sided perspectives relative to two key distinctions. In the first perspective it is assumed that the major impact is of computing on society rather than society on computing. This takes for granted Ellul's (1964) view of technology as autonomous, and fails to question why the technology itself has arisen out of the processes of society. In the second perspective it is assumed that the future may be projected as an extrapolation of processes begun in the past. This takes for granted the causal models fundamental to physical science and fails to recognise the higher level goals that lie behind computing developments seen as part of the teleology of society.

These one-sided perspectives are appropriate to the analysis of technological dependencies such as the impact of low-cost high-speed data-analysis techniques on structural design. However, they are not appropriate perspectives from which to evaluate the relations between computing, society, and design. These are phenomena of the *life world* (Schutz and Luckmann, 1973) and embedded in its processes. To understand their relations to computing we must view computing also as a phenomenon of the life world embedded in the processes of the life world, both generated by them and generating them (Blum and McHugh, 1984; Kohak, 1984).

Viewed as a causal chain, the development of computing technology is highly indeterminate. Technological forecasts for computing are notoriously inaccurate (Withington, 1974; Gaines, 1984a). Projections of the technology over more than a few years are meaningless. Each month the technical press contains a number of major surprises. The causal model is not appropriate to a phenomenon governed by social needs and hence directed by the goals of society. The past is not an adequate determinant of the future in these circumstances. A teleological model in which society is viewed as moving towards some future situation is more appropriate to the processes of the life world. The cascade of subgoals generated to create that future situation accounts for the activities of the past, generates those of the present, and determines those of the future. The determinacy, however, is that of a goal-seeking adaptive system. It predicts the necessary achievements but not the means by which they will be achieved.

Computing technology is directed by the processes of society at least as much as it impacts them. Up to its present fairly primitive stage, its development has been governed by existing social processes and the dominant value system. It is only just beginning to become an agent for change. The perspective that views only the impact of computing on society misses the major dynamics of computing technology during the past forty-five years. The social needs underlying computing result from increasing world population and integration leading to an increasingly complex society. In *Trust and Power*, Luhmann (1979) postulates *complexity-reduction* as the fundamental motivation for all our social institutions. We assume roles to simplify our interactions with one another. We use technology to simplify the natural world, creating man-made environments that we can understand and control. In *Future Positive* De Bono (1979) suggests that computer technology was developed to aid us in coping with the increasing complexity of society. The computer is to the organisation revolution what steam power was to the industrial revolution. The computer extends our organising power in the same way as steam engines extended muscle power.

The infrastructure of computing as a recursive learning process

In coming to understand computing technology, it is important to realise that the electronic computer itself is only one component in an elaborate and highly differentiated infrastructure. This infrastructure has grown through a succession of *generations* of computers, each of which represents a major change in computing technology (Gaines, 1984b). During the eight-year span of each computing generation, revolutionary changes have taken place that correspond in magnitude to those taking place over some seventy years or more in the aircraft industry. The first generation commenced in 1948 and we are now in the fifth generation spanning 1980 through 1987.

The development of the infrastructure of computing can be modeled using the most significant concept underlying computing itself, that of *recursion*. This enables the formation of complex processes through the interaction of a few primitive functions that generate complexity from simplicity by referencing themselves. From a mathematical point of view, computing science is founded upon the theory of recursive functions. The notions of recursion and self-reference, and the analysis of complex systems as generated by the recursive application of self-referential functions, have proved very powerful in the analysis of many significant systems, including the physical world, biological organisms, societies, and human consciousness.

The growth of the infrastructure of computing technology may be seen as the recursive application of the basic process underlying social and individual development: that of *learning* (Gaines and Shaw, 1984a). Marchetti (1981) has shown that treating society as a learning process leads to simple explanations of socioeconomic processes such as business cycles and technology substitution. The introduction of any new knowledge, technology, or product follows a logistic *learning curve* in which growth takes off slowly, begins to climb rapidly, and then slows down as all the information has been assimilated (van Dujin, 1983). The shape of the curve corresponds to the initial need to have knowledge in order to acquire more and the final slowing down in the acquisition as there is less and less left to acquire.

Learning curves and the infrastructure of computing

It has been noted in many disciplines that the qualitative phenomena during the growth of the logistic curve vary from stage to stage (Crane, 1972). If we take the amount of knowledge necessary for a mature technology to be 100%, then the 10%, 25%, 50%, 75%, and 90% points are equally spaced in time along the logistic curve. These points mark significant phases in knowledge acquisition.

1 When less than 10% of the knowledge is available, little can be achieved. We are in a *prebreakthrough* period in which most projects attempted will fail through lack of some critical information or skill.

2 At around the 10% level, some form of recognisable breakthrough becomes possible and we move into a phase of *replication* in which the breakthrough activity is noted and mimicked widely with little understanding.

3 Replication leads to increasing experience and knowledge based upon it, and when the 25% level is reached sufficient information is available for a phase of *empiricism* in which design rules are formulated on the basis of experience.

4 At the 50% level, sufficient information has been accumulated for deeper patterns to be discerned, and a phase of *theory* commences in which causal rules are derived that allow further experience to be predicted and design rules to be derived.

5 At the 75% level, the theories have become accepted as the normative basis for further progress and an *automation* phase starts in which they are used for design and to search out the residual knowledge.

6 Above the 90% level, a *phase of maturity* is entered when the knowledge is expected to be available and used routinely.

This *learning curve model* may be applied to the substitution of different electronic device technologies (EDTs) as a basis for computing. It then distinguishes the generations of computers in terms of the technology in use.

0 The zeroth generation started in 1940 with the relay-based Bell Complex Number Computer followed in 1941 by the Zuse Z3.

1 The first generation started in 1948 with the vacuum-tube-based BINAC in the United States of America and EDSAC in the United Kingdom.

2 The second generation started in 1956 with the transistor-based Bell Leprachaun followed in 1959 by the RCA 501.

3 The third generation started in 1964 with the IBM 360 family using some integrated circuits.

4 The fourth generation started in 1972 with the use of large-scale integration in the main memory of the IBM 370/158 and in the Intel 8008 8-bit microprocessor.

5 The fifth generation started in 1980 with the use of very large-scale integration by IBM to put the 370 processor on a chip followed by the HP-9000 in 1981 with 450 000 transistors on a chip.

6 Projecting the eight-year cycle of generations has the sixth generation starting in 1988 with ultra-large-scale integration and some 10 million transistors on a chip.

7 Projecting further has the seventh generation starting in 1996 with grand-scale integration and 1000 million transistors on a chip.

Qualitative changes in the nature of computing

The definition of generations in terms of EDT captures some important aspects of computing technology, such as cost decreases, size decreases, power increases, and so on. However, it fails to account for the *qualitative* changes that have given computing its distinct character in each generation. The change from mechanical to electronic devices made it possible to store programs as data and enabled the use of computers as a general-purpose tool and then the development of programming language compilers. The transistor made reliable operation possible and enabled routine electronic data processing and then interactive time-sharing. Integrated circuits reduced costs to the level where computers became common-place and made possible the personal computer dedicated to a single user. What is missing from the model of computing developing through successive generations of EDT is the infrastructure that has been built above this. A complete account of the development of the computing industry must be two-dimensional with breakthroughs in key system technologies also represented. Figure 1 shows this infrastructure with the phases on the learning curve of EDT at the base and successive computing technologies above it as the infrastructure.

Now the generations may be defined in terms of major qualitative changes.

0 The initial breakthrough in EDT leading to the zeroth generation is placed at 1940 about the time of the Atanasoff and Berry experiments with tube-based digital calculations.

1 The first generation breakthrough was the introduction by Mauchly and von Neumann of stored program and subroutine concepts around 1947, which led to the transition from the ENIAC to the EDVAC designs. This detached computing as a separate discipline from electronics by substituting software for hardware in a *virtual machine architecture* (VMA).

2 The second generation breakthrough was to bridge the gap between machine and task through the development of *problem-orientated languages* (POLs) such as FORTRAN around 1956.

3 The third generation breakthrough was to bridge the gap between the computer and the person with the development of *interactive* time-shared computers in 1964 allowing close *human-computer interaction* (HCI).
4 The fourth generation breakthrough was in the early 1970s with developments in *expert systems* based on *knowledge-processing*. Such *knowledge-based systems* (KBSs) have the capability to store information through its interrelations and make inferences about its consequence.
5 The fifth generation breakthrough was in 1980 with developments in machine learning and *inductive inference systems* (IISs).
6 We speculate that the growth of robotics will provide the next breakthroughs in which goal-directed mobile computational systems will act autonomously to achieve their objectives. The breakthrough into the sixth generation era commencing in 1988 will be one of *autonomous activity systems* (AASs).
7 The interaction between these systems will become increasingly important in enabling them to cooperate to achieve goals and the seventh generation era commencing in 1996 will be one of *socially organised systems* (SOSs).

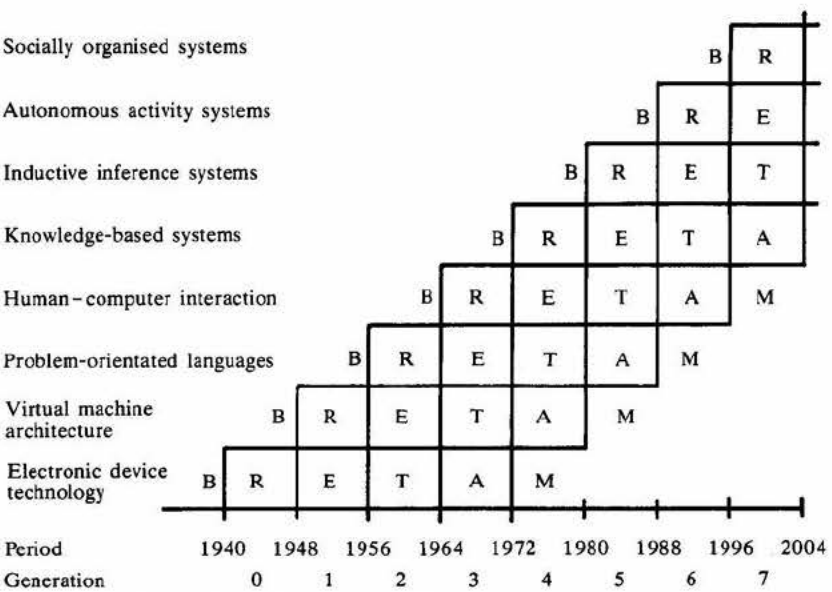

Figure 1. Eight generations of computers and their underlying technologies.

Invention, research, and products through the generations

The model of the development of computing described above is important in any evaluation of the impact of computing. Each generation represents a revolution in technology with a qualitatively different impact. Each generation subsumes the capabilities of that preceding it, providing very much better facilities at very much lower cost, and adding new capabilities not possessed by the previous generations. The availability of these new capabilities in a generation is linked to the stage of the learning curve for each technology in that generation.

Invention is focused at the BR interface (see figure 1) where new breakthrough attempts are being made on the basis of experience with the replicated breakthroughs of the technology below.
Research is focused at the RE interface where new recognised breakthroughs are being investigated using the empirical design rules of the technology below.
Product Innovation is focused at the ET interface where new products are being developed on the basis of the empirical design rules of one technology and the theoretical foundations of the technology below.
Established Products are focused at the TA interface where product lines can rest on the solid theoretical foundations of one technology and the automation of the technology below.
For example, in the fourth generation (1972-1979):
BR: recognition of the knowledge-acquisition possibilities of KBS led to the breakthrough to inductive-inference systems;
RE: research focused on the natural representation of knowledge through the development of HCI, for example, the Xerox Star direct manipulation of objects;
ET: experience with the HCI using the POL BASIC led to the innovative product of the Apple II personal computer;
TA: the simplicity of the POL RPG II led to the design of the IBM System/3 product line of small business computers.
In the current fifth generation (1980-1987):
BR: recognition of the goal-seeking possibilities of IIS is leading to the breakthrough to autonomous-activity systems in robotics;
RE: research is focused on learning in KBS;
ET: the advantages of the nonprocedural representation of knowledge for HCI led to the innovative designs of the Visicalc spread-sheet business product and the LISP machine scientific product;
TA: the ease of HCI through a direct manipulation POL led to the Apple Lisa/Macintosh product line of personal computers.

CAD through the generations

Computer-based product families targeted on particular market requirements such as computer-aided design follow the trajectories in the development of computing itself. Research activities attempt to apply computing technologies at the RE interface to the requirement. Innovative products are based on the new technologies available at the ET interface. Established products tend to use technologies only up to the TA interface. There are learning curves associated with the applications of the technologies to particular requirements, and with the rate at which these products are purchased and brought into use. Thus, computer applications tend to lag developments in the basic technologies, but follow the same basic pattern of qualitative change.

The early generations of computers could impact only the analysis aspects of design. The first generation provided virtual machines that could be programmed for the numerical calculations underlying various types of analysis. The development of problem-orientated languages in the second generation made it easier to establish libraries of such programs. However, the designer could access the results only indirectly until the third-generation development of direct human-computer interaction. These developments became available in innovative products during the fourth generation, and interactive CAD terminals are now routine product lines in current fifth-generation systems.

Computing systems also became increasingly involved in the action aspect of design as improved reliability in the third and fourth generations allowed them to

be used in the direct control of equipment. Computer-aided manufacturing (CAM) is now at a stage where many products can be designed at a CAD terminal and manufactured on a CAM system with little human intervention between the designer and the final product.

The goal development and creative aspects of design have been little impacted by computers until recently. The potential of computers to influence human creativity was very low through the first three generations. The capabilities for effective human–computer interaction appearing in fourth-generation products and those for knowledge processing appearing in fifth-generation products are both necessary to support the creative process (Shaw and Gaines, 1985). *Expert systems* are now coming into widespread use that involve the computer-based system in advising the human user about complex decisionmaking processes (Gaines and Shaw, 1984b). Goal development in particular is well suited to this type of interaction and we can expect to see increasing use of such systems at the early stages of the design process. Often it will be the clients who interact with the system, refining their requirements prior to establishing design goals.

Current expert systems encode the expertise of people and make it more widely available. Access to this expertise may encourage users to be more creative, but the system itself has no direct role to play in the creative process. However, the inductive-inference capabilities now being researched will enable sixth-generation systems to suggest new hypotheses and views of the world. The autonomous-activity capabilities expected to be the next breakthrough will enable seventh-generation products to suggest alternative subgoals in order to achieve an overall objective.

Thus, despite the significance of computing in the analysis aspects of design, it is reasonable to view the current stage of computer development as still being fairly primitive. Computers do not yet have the critical capabilities necessary to play a major role in the design process. Drucker (1978) compares the development of the electricity industry with that of the information industry, making the analogy that "information is energy for mind work" (page 27). He remarks that if it had been fashionable to speak of generations of generators then there "would have been a 'fifth-generation' or 'sixth-generation' generator before there was any widespread use of electric power" (page 24). It was the invention of the light bulb that led to the use of electricity as a universal form of energy. It is emulation of human knowledge-processing capabilities that will lead to the use of computing as a universal extension of the mind.

We suggest that the social needs leading to the development of computing technology will only begin to be satisfied in the sixth and seventh generations. Design is one of the highest levels of human activity. We now live largely in a human-designed and human-made world. The complexity of our world is increasing and it is evolving beyond our capabilities to design and control. Future-generation computing systems will provide extensions to our minds, enabling us to cope with increasing complexity and understand the consequences of design decisions that are increasingly significant in shaping our world (Shaw and Gaines, 1984).

Conclusions

Computing technology may be viewed as autonomously impacting society. However, it may also be viewed as a product of society, created through its needs and moulded by its values. From this second point of view, the development of computing may be modeled as a succession of social learning processes arising out of the need to cope with an increasingly complex world. This gives rise to

successive generations of computers with qualitatively different capabilities. Only now in the fifth generation and beyond are computing systems becoming able to interact with people at the levels of the higher processes of the mind. Thus, their major impact on design is yet to come.

Acknowledgement. Financial assistance for this work has been made available by the National Sciences and Engineering Research Council of Canada.

References

Bell D, 1973 *The Coming of Post-industrial Society* (Basic Books, New York)
Blum A, McHugh P, 1984 *Self-reflection in the Arts and Sciences* (Humanities Press, Atlantic Highlands, NJ)
Brod C, 1984, *Techno Stress: The Human Cost of the Computer Revolution* (Addison-Wesley, Reading, MA)
Crane D, 1972, *Invisible Colleges: Diffusion of Knowledge in Scientific Communities* (University of Chicago Press, Chicago, IL)
De Bono E, 1979 *Future Positive* (Maurice Temple Smith, London)
Dizard W P, 1982 *The Coming Information Age: An Overview of Technology, Economics and Politics* (Longman, New York)
Drucker p F, 1978 *The Age of Discontinuity* (Harper and Row, New York)
van Dujin J J, 1983 *The Long Wave in Economic Life* (George Allen and Unwin, Hemel Hempstead, Herts)
Ellul J, 1964 *The Technological Society* (Vintage Books, New York)
Gaines B R, 1984a, "A framework for the fifth generation" *Proceedings of National Computer Conference* (AFIPS Press, Arlington, VA) **53** 453-459
Gaines B R, 1984b, "Perspectives on fifth generation computing" *Oxford Surveys in Information Technology* **1** 1-53
Gaines B R, Shaw M L G, 1984a, "Generations of computers: modeling and forecasting" *Possible Worlds* **1**(4) 3-16
Gaines B R, Shaw M L G, 1984b *The Art of Computer Conversation: A New Medium for Communication* (Prentice-Hall, Englewood Cliffs, NJ)
Kohak E, 1984 *The Embers and the Stars: A Philosophical Enquiry into the Moral Sense of Nature* (University of Chicago Press, Chicago, IL)
Luhmann N, 1979 *Trust and Power* (John Wiley, Chichester, Sussex)
Marchetti C, 1981, "Society as a learning system: discovery, invention and innovation cycles revisited" RR-81-29, International Institute for Applied Systems Analysis, Laxenburg, Austria
Mowshowitz A, 1976 *The Conquest of Will: Information Processing in Human Affairs* (Addison-Wesley, Reading, MA)
Schutz A, Luckmann T, 1973 *The Structures of the Life-World* (Heinemann Educational Books, London)
Shaw M L G, Gaines B R, 1984, "Fifth generation computers as the next stage of a new medium" *Proceedings of National Computer Conference* (AFIPS Press, Arlington, VA) **53** 445-451
Shaw M L G, Gaines B R, 1985, "Developments in dialog engineering" *Proceedings of National Computer Conference* (AFIPS Press, Arlington, VA) **54** 493-499
Toffler A, 1980 *The Third Wave* (Bantam Books, New York)
Turkle S, 1984 *The Second Self: Computers and the Human Spirit* (Simon and Schuster, New York)
van Dujin J J, 1983 *The Long Wave in Economic Life* (George Allen and Unwin, Hemel Hempstead, Herts)
Weizenbaum J, 1976 *Computer Power and Human Reason: From Judgement to Calculation* (W H Freeman, New York)
Wiener N, 1950 *The Human Use of Human Beings* (Riverside Press, Cambridge, MA)
Withington F G, 1974, "Five generations of computers" *Harvard Business Review* **52** 99-108

p

© 1986 a Pion publication printed in Great Britain