FROM ELECTRONICS TO FIFTH GENERATION COMPUTING: THE INFRASTRUCTURE OF THE COMPUTING INDUSTRY

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A model of the development of the computing industry is described and used to account for past events and predict future trends. Underlying all developments in computing is a tiered succession of learning curves which make up the infrastructure of the computing industry. The paper provides a framework for the industry based on this logical progression of developments. It links this empirically to key events in the development of computing. It links it theoretically to a model of economic, social, scientific and individual development as related learning processes with a simple phenomenological model. It uses this model to account for past developments in computing and extrapolates it to predict future trends.

Introduction

Computer technology changes rapidly and we have become used to being surprised. In a world of change and surprise how much, and how far into the future, can we predict? We can see patterns, for example, in the development of circuit technology, from relays through vacuum tubes, transistors, integrated circuits, large-scale integration and so on. We may notice significant events in the history of computing, for example the concept of programmability, the release of FORTRAN, the availability of timesharing, the creation of MYCIN, the announcement of a fifth generation development program, and so on. We can identify changing foci of attention, databases, structured programming, personal computers, expert systems, and so on. Are these significant? Do they form part of a larger pattern of development of our industry? Can we use this pattern to structure the past in a simple and meaningful way? Can we project it into the future and predict possible worlds to come?

This paper answers to these questions. It arises from a study of key events in the the computing industry and their relationship to business cycles. It provides a framework for the computer industry that shows a logical progression of developments. It links this empirically to key events in the development of computing. It relates it theoretically to a model of economic, social, scientific and individual development as related learning processes with a simple model. It uses this model to account for past developments in computing and extrapolates it to predict future trends.

The Learning Curves for New Technologies

The introduction of any new knowledge, technology or product follows a **learning curve** in which growth takes off slowly, begins to climb rapidly and then slows down as all the information has been assimilated. Such **logistic** curves arise in many different disciplines such as education, ecology, economics, marketing and technological forecasting [26]. They are the outcome of any systemic process in which the rate of growth is proportional to the amount: a) already accumulated; and b) remaining to accumulate. In technological terms then the two components correspond to: a) needing to have knowledge in order to acquire more; and b) slowing down in the acquisition as there is less left to acquire.

It has been noted in many disciplines that the qualitative phenomena during the growth of of the logistic curve vary from stage to stage [6]. 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 curve. They mark significant phases in knowledge acquisition:

- When less than 10% of the knowledge is available, little can be achieved. We are in a pre-**breakthrough** period where most projects attempted will fail through lack of some critical information or skill.
- At around the 10% level some form of recognizable breakthrough becomes possible and we move into a phase of **replication** in which the breakthrough activity is noted and mimiced widely with little understanding.
- 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 based on experience.
- 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.
- 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.
- Above the 90% level a **phase of maturity** is entered when knowledge is available and used routinely.

Fitting logistic curves to historic data gives a very precise account of the development of major technologies such as the successive substitutions of one form of energy production for another [19]. Such substitutions give rise to a tier of learning curves each building upon one another and it is the **envelope** of these that we see as the improving performance of the technology in time [1]. This is what has happened in electronic device technology where relays were replaced by vacuum tubes in the 1940s, by transistors in the 1950s, by integrated circuits in the 1960s, and so on. Each new technology has had its own learning curve and hardware-based performance parameters such as speed of operation have shown a steady improvement based on the envelope of these learning curves.

A Structural Model of Computing Developments

The learning curve model for the substitution of different electronic technologies as a basis for computing is effective in demarcating the first three generations of computers. It distinguishes generations of computers in terms of the technology in use:

- The zeroth generation started in 1940 with the relay-based Bell Complex Number Computer.
- The first generation started in 1948 with the vacuum tube-based EDVAC in the USA and EDSAC in the UK.
- The second generation started in 1956 with the transistor-based Bell Leprechaun.
- The third generation started in 1964 with the IBM 360 family using some integrated circuits.
- 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.
- 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.
- Projecting the 8-year cycle of generations has the sixth generation starting in 1988 with ultra large-scale integration and 10 million devices on a chip.
- Projecting further has the seventh generation starting in 1996 with grand-scale integration and 1,000 million devices on a chip [23].

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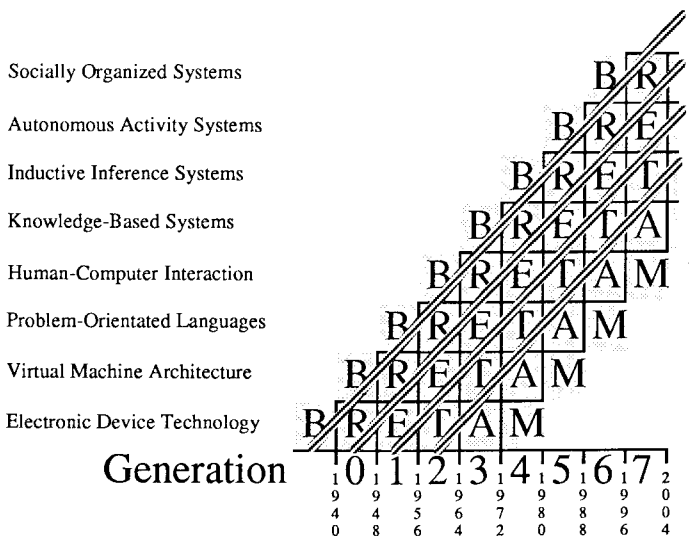

Fig. 2 Invention, research & products through generations of computers

for inferring chemical structures from mass-spectrometry data and MYCIN [25] for the diagnosis of microbial infections in the early 1970s. It led to a spate of expert system development in the fourth generation era of the 1970s [14], and pragmatic design rules for knowledge engineering in the current fifth generation era [17]. The utilization of their massive VLSI production capability [9,13] for the support of KBS through LISP [3] and PROLOG [5] machines is the other major priority in the fifth generation program [22].

Defining the upper levels of the infrastructure becomes more and more speculative as we move into the immediate past of our own era and look for evidence of learning curves that are at their early stages. It is reasonable to suppose that the level above the representation and processing of knowledge in the computer will be that of knowledge acquisition, breakthroughs in machine learning and inductive inference systems (IIS). Two breakthroughs in this area have been Lenat's **AM** learning mathematics by discovery [7] and Michalski's inductive inference of expert rules for plant disease diagnosis [21]. In the current fifth generation era machine learning has become a highly active research area still in its replication phase [20].

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** (AAS). We speculate further that interaction between these systems will become increasingly important in enabling them to cooperate to achieve goals and that the seventh generation era commencing in 1996 will be one of **socially organized systems** (SOS).

Invention, Research, Product Innovation, & Product Lines

The horizontal BRETAM learning curve for each level of the infrastructure in Fig. 1 is echoed by a vertical BRETAM cross-section representing the different stages of each of the main technologies in each generation. The interface between technologies in each generation determines the focus of attention for different types of activity as shown in Figure 2:

- **Invention** is focused at the BR interface where new breakthrough attempts are being made based on experience with the replicated breakthroughs of the technology below.
- **Research** is focused at the RE interface where new recognized 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 based on 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.

In the zeroth generation: 1940-47:
- **BR:** recognition of the potential of EDT led to the breakthrough to the stored program and virtual machine architecture.

In the first generation: 1948-55:
- **BR:** recognition of the capabilities of subroutines to extend the VMA led to the breakthrough to the problem-orientated language;
- **RE:** research focused on increasing the capabilities of the VMA to take advantage of advances in hardware development.

In the second generation: 1956-63:
- **BR:** recognition of the advantage of making the POL directly control the machine led to the breakthrough to direct human-computer interaction;
- **RE:** research focused on increasing the capability of POLs to take advantage of advances in VMAs.
- **ET:** experience with the potential of the VMA led to the product design innovation of virtual memory hardware in the ATLAS computer.

In the third generation: 1964-71:
- **BR:** recognition of the knowledge engineering possibilities of HCI led to the breakthrough to knowledge-based systems;
- **RE:** research focused on the improvement of the HCI through the development of interactive languages.
- **ET:** experience with the POL ALGOL60 led to the innovative VMA of the Burroughs B6500 computer;
- **TA:** the emulation capability of the VMA led to the design of the IBM360 product line of mainframes.

In the fourth generation: 1972-79:
- **BR:** recognition of the knowledge acquisition possibilities of KBS led to the breakthrough to inductive-infererence systems;
- **RE:** research focused on the natural representation of knowledge through the development of HCI.
- **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 business computers.

In the current fifth generation: 1980-87:
- **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 non-procedural 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.

In the coming sixth generation: 1988-95:
- **BR:** the recognition of cooperative goal-seeking possibilities of AAS will lead to the breakthrough to socially-organized systems in robotics;
- **RE:** research will focus on goal-seeking in robots learning about their environment;
- **ET:** innovative products will use inductive inference to set up KBSs;
- **TA:** expert systems will become established product lines.

In the speculative seventh generation: 1996-2003:
- **BR:** speculation on the 1996 breakthrough is left as an exercise to the science fiction writer.
- **RE:** research will be focused on the social interaction of autonomous robots;
- **ET:** innovative products will be based on goal-directed autonomous robots;
- **TA:** learning systems will become established products, e.g. an encyclopaedia that generates new knowledge from inferences based on combining entries.

This model of the focus of attention in the computing industry accounts for the changes in fashions in research, innovative products and product lines through the generations. It also accounts for the qualitative differences in each generation between the types of system in research laboratories, innovative products and mature product lines.

The model can be applied not only to the overall industry but also to specific application areas. For example in computer-aided design (CAD) the initial developments were in analytic systems taking advantage of the basic processing power of computers. The next generation of CAD systems used special-purpose high-level languages specific to the CAD problem area. The next generation introduced interactive design. The current generation is beginning to use expert system techniques to offer advice to the designer. We predict that the next generation of CAD systems will use inductive inference to model the behavior of designers and improve the support offered.

Conclusions

Underlying all developments in computing is a succession of learning curves which make up the infrastructure of the computer industry. The base curve is that for electronic device technology and above it are those for: virtual machine architectures; problem-orientated languages; human-computer interaction; knowledge-based systems; inductive inference systems; autonomous activity systems; and socially organized systems. In each generation the types of breakthrough, research focus, product innovation, and establisned product lines, may be predicted from the levels of technologies in particular phases. This gives an account of past inventions, fashions in research, innovations in products and launches of product lines. It also gives a reasonable basis for forecasting future trends in the fifth, sixth and seventh generations.

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