SOCIO-ECONOMIC FOUNDATIONS OF KNOWLEDGE SCIENCE

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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, particularly fifth and sixth generation priorities. The industry came into being as electronic device technology enabled the social need to cope with an increasingly complex world to be satisfied. 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. The fifth generation development program with its emphasis on HCI and AI, and the sixth generation program with its emphasis on knowledge science are natural developments in the foci of attention indicated by the model.

INTRODUCTION

When the Japanese Fifth Generation Computing System (FGCS) development program was announced in 1982 great emphasis was placed on artificial intelligence (AI) and the development of advanced human-computer interaction (HCI) [40]. However, the ICOT research activities have concentrated on machine architectures for knowledge-based systems based on high speed Prolog and relational database machines [32] involve no direct research on AI or HCI [17]. The publication in 1985 of the Sixth Generation Computing System (SGCS) [5,18,48] development proposal shows a serious intention in Japan to go beyond current FGCS activities and tackle the AI and HCI aspects of computing on a broad front.

The term "sixth-generation computing proposal" is the name used by the Japanese press [28] and some computer scientists [41] for the report, *Promotion of R&D on Electronics and Information Systems that may Complement or Substitute for Human Intelligence*, from the Subcommitte on Artificial Intelligence of The Council on Aerospace and Electronics Technology in Tokyo. The Council was asked by the Ministry of Science and Technology in January 1983 to report on AI in these terms. It formed a sub-committee that met twelve times in preparing this report, used the term *knowledge science* for its subject matter, and reported in March 1985. The English translation comprises some 18,000 words.

The SGCS proposal is one component of a range of government-supported information technology programs in Japan [41] as shown in Figure 1. More importantly is also part of the proposed *Human Frontier Program* being initiated in Japan but involving international collaboration by a worldwide research network [6,29] as shown in Figure 2. The SGCS program has significant components of accelerated *research acceleration* involving a *fusion of disciplines* and leading to *hybrid sciences*. It is the computer component of work on the brain's higher functions. It is not clear if the Human Frontier Program and its SGCS component will proceed as specified, but the objectives and program structure are significant, innovative contributions to scientific research strategy, and will affect the objectives and strategies of related research worldwide.

Ministry of International Trade and Industries	1966-71 Super computer ($40M) 1971-80 Pattern information processing system ($90M) 1971-76 Computer system development 1976-79 VLSI ($120M) 1979-84 New OS and peripherals which handle the Japanese language 1981-90 Super computer—fourth generation ($100M) 1982-91 Fifth generation computer ($200M) 1983-90 Robotics: extreme environments; flexible arms; 3D visual recognition 1985-90 Sigma project: economic software production for industry
Science and Technology Agency	1982-85 Machine translation ($3M) 1986- Sixth generation system—AI and human brain function research
Ministry of Postal Services	1986-02 Intelligent telephone system with simultaneous translation ($400M)
Ministry of Education	1984-86 Intelligent processing of knowledge information in multi-media ($2.5M) 1986-88 Basic research on advanced natural language processing ($2.5M) 1987- Software technology

Figure 1 Japanese Government Computing Programs

Four objectives are specified for promoting knowledge science: innovations in *frontier high technologies*; *economic and cultural advancements*; *contributions to the expansion of human potential*; and *establishing a foundation for creative science*. The most surprising feature of the proposed research program is that it moves outside the boundaries of computing technology and is based on inter-disciplinary interaction with physiology, psychology, linguistics and logic. The report analyses the state of the art in these four relevant sciences and proposes the development of eight technologies based on them for application in four major areas as shown in Figure 3. The application areas do not differ from those of the FGCS program but the path specified to them is far more foundational.

This path through the brain and human sciences to future generation computing was previewed in an interview with Fuchi, the Director of ICOT, when in reply to the question:

> "Are you saying that the design of the fifth-generation may be modeled by learning more about the human thinking process?"

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Human Frontier Program

- Four billion dollars over twenty years
  — Japan will fund initial stage worldwide
- Positive contribution to global society
  — International collaboration
  — Worldwide research network
  — Systematic acceleration of research
  — Fusion of disciplines
  — Hybrid sciences
- Creative and basic research
  — Environmental pollution
  — Diminishing resources
  — Ageing
  — Over-population
- Brain's higher functions
  — Memory
  — Judgement
  — Immune system

Figure 2 The Human Frontier Program

he answered:

> "Yes, we should have more research on human thinking processes, but we already have some basic structures. For more than 2000 years man has tried to find the basic operation of thinking and has established logic. The result is not necessarily sufficent; it's just the one that mankind found. At present we have only one solution - a system like predicate calculus. It is rather similar to the way man thinks. But we need more research. What, really, is going on in our brain? It's a rather difficult problem." [14]

The FGCS program has been targeted on the development of very high-speed deductive reasoning machines using predicate calculus as a knowledge-representation language. However, standard logic bears only a remote resemblance to human reasoning processes [52]. Modern formal logic was developed as a foundation for mathematics just because mathematical rigor is so foreign to everyday human activity [39]. Causal models may be incapable of encompassing the processes of biological systems, and currently we have no formalism in which to express the anticipatory dynamics of living systems [43]. What is going on in our brain is certainly a difficult problem but the development of advanced AI and HCI demands that we resolve it. The SGCS proposal sets out to do this and makes no detours to avoid using words such as *"intuition, analogy and creativity"* in its description of human reasoning capabilities.

It was not easy for those in the computing industry to accept the concept in the FGCS proposal that AI research was sufficiently advanced to be the basis for a next generation of computing systems. It will be even more difficult to assimilate the concept in the SGCS proposal that physiology, psychology, linguistics and logic are the proper scientific foundations for these systems. Few industrial research groups or university computing science departments have staff qualified in these disciplines. How has computing come to the stage where it is at all reasonable to consider these sciences as fundamental to its development?

This paper traces the development of generations of computers and gives a model of the infrastructure of the computing industry which answers this question and links it empirically to key events in the development of computing.

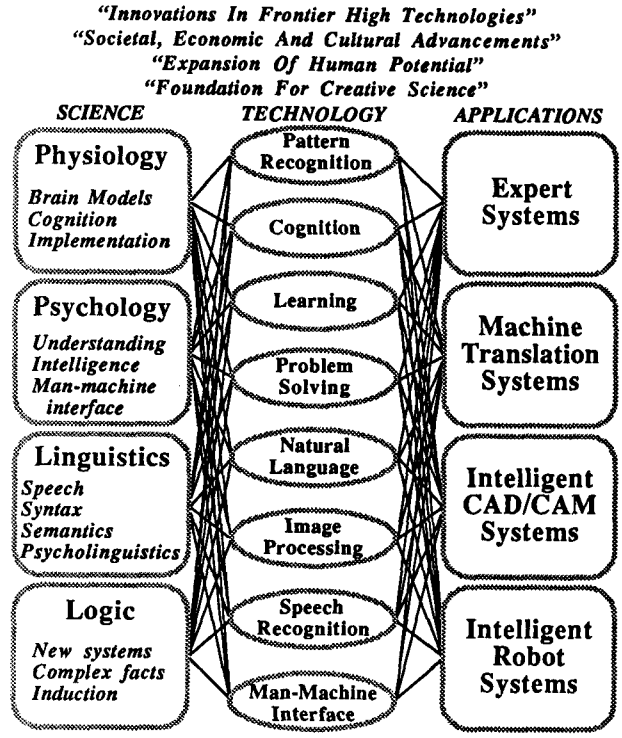

Figure 3 Sixth Generation Computing Program

SYSTEMIC FOUNDATIONS OF COMPUTING

There is a systemic model of the development of the computer industry. The precursors necessary to the birth of a new industry are a social need and a technology capable of satisfying it. The need allows a market to be generated. The technology allows products to be created for that market. The technology enabling computers was electronics. The key operational concepts of a digital computer date back at least to Babbage, Lovelace and Boole in the nineteenth century [25]. However, the mechanical technology of their time could not support a digital computer.

The social need for computation in Babbage's time was navigation and its support through astronomical calculations. The enabling technology of electronic devices dates to the early 1900s with De Forest's development of the triode vacuum tube [47]. However, it was not until the outbreak of World War 2 generated the need for rapid calculation of trajectories that the social requirement for computation became sufficiently urgent. Mechanical device technology in the ball and disk differential analyser had been taken to its limit and was inadequate. The pressures created by the urgent need to find an alternative technology supporting computation led to the use of vacuum tubes in the design of ENIAC by Mauchly and Eckert [49].

The following sections present a model of the development of the computer industry as a tiered succession of learning curves of new technologies.

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 [34]. They are the outcome of any systemic process in which the rate of growth is proportional to the amount: already accumulated; and remaining to accumulate. If we think of these in technological

that we see as the improving performance of the technology in time. This is what has happened in the base technology underlying computing 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 [1].

STRUCTURAL MODEL OF COMPUTING

The learning curve model for the substitution of different electronic technologies is very effective in demarcating the first three generations of computers. The zeroth generation started in 1940 with the relay-based Bell Complex Number Computer followed in 1941 by the Zuse Z3. The first generation started in 1949 with the vacuum tube-based BINAC in the USA and EDSAC in the UK. The second generation started in 1956 with the transistor-based Bell Leprachaun followed in 1959 by the RCA 501. 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 some 10 million transistors on a chip and the seventh generation in 1996 with grand-scale integration and 1,000 million on a chip [42].

This definition of generations in terms of hardware works well for the zeroth through second generations because of the distinct qualitative changes involved. However, as Rosen notes in his analysis of computer generations it blurs thereafter and "we are faced with an anomalous situation in which the most powerful computers of 1979-1980, the CDC Cyber 176 and the CRAY 1, would have to be assigned to the second and third generations, respectively, while the most trivial of hobbyist computers would be a fifth-generation system" [44]. The reason for this anomaly is that the substitution effects of one form of technology for another are gradual and do not generate hard boundaries. The enabling effects of changing technologies are far more dramatic: 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 timesharing; integrated circuits reduced costs to the level where computers became commonplace and made possible the personal computer dedicated to a single user.

The pattern is one of improvements in the basic technology allowing new developments to occur in the architecture and applications of systems based on it. What is missing from the model of computing developing through successive generations of electronic device technology (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 4 shows this infrastructure with the phases on the learning curve of EDT at the base and successive computing technologies above it as the infrastructure.

The 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. Experience was gained with COLOSSUS and ENIAC during the next eight years leading to a spate of empirical designs in the 1956-63 period, theoretical foundations for logic minimization and automata theory, automation with computer-aided design tools,

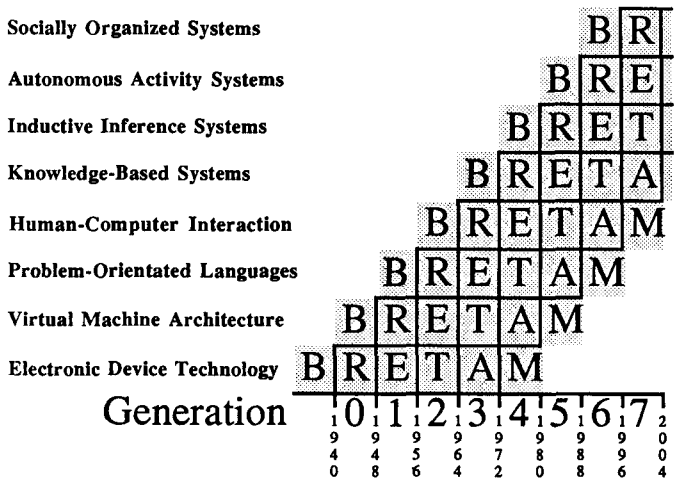

Figure 4 The Infrastructure of Computing

and culminating into maturity with the 4004/8008 microprocessor chips in 1971/1972. The number of devices on a chip follows Moore's law in doubling each year through the second and third generations, and has continued to double every 1.5 years through the fourth and fifth generations [42]. Automation has reached the extreme level where silicon compilers allow a designer to implement his ideas directly in EDT with little further human intervention [13].

The first breakthrough generating a computing infrastructure was the introduction of the stored program concept which led to the transition from the ENIAC to the EDVAC designs. The key concepts were discussed by Mauchly in his paper of 1947 [36] where he noted that stored programs the machine instruction set to be extended. This was the key conceptual breakthrough in computer architecture, that the limited functionality provided directly by the hardware could be increased by programs called as subroutines, and that the hardware and routines together may be regarded as a new machine. This is the foundation of the development of a variety of forms of virtual machine architectures (VMAs) [53] that separates out computing science as a discipline from other areas of electronic applications. In the fifth generation era the virtual machine technology has become a mature foundation for advanced system design in human factors and knowledge engineering [16].

The next level of breakthrough was to bridge the gap between machine and task through the development of problem-orientated languages (POLs). The foundations of these in the first generation era were subroutine libraries that provided VMAs closer to the problem requirements, notably floating point arithmetic and mathematical functions. Work on the design of FORTRAN in 1954 and its issue in 1957 marks the beginning of the second generation era with languages targeted to specific problem areas of business data processing, text processing, database access, machine tool control, and so on. A 1968 paper on the coming fourth generation notes that "programming today has no theoretical basis" and calls for a scientific basis in the next generation [51]. Sure enough the theory linking POLs to the underlying VMAs developed during the fourth generation era, for example, that of abstract data types and initial algebras

[24]. In the fifth generation era the application of experience, design rules and theory to the automation of software production has become the top priority [2].

The binary VMA-POL relationship bridges the gap between the computer and its application. However, the computer industry is based on the triadic relationship between computer, application and person, for example, programmer, system analyst and user. The next level of breakthrough was to bridge the gap between the computer and the person with the development of interactive computers. The move from batch-processing to direct human-computer interaction (HCI) was made in 1963/1964 with the implementation of MIT MAC, RAND JOSS and Dartmouth BASIC systems [19]. The study of such systems led to design rules for HCI in the 1970s [26] and theoretical foundations have started to emerge in the 1980s [21]. The improvement of HCI is a major priority in the Japanese FGCS program [31].

The third element in the triadic relationship between computer, application and person is that between the application and the person. It is one of knowledge-processsing, the human capability to store information through its inter-relations and make inferences about its consequences. The breakthrough in knowledge-based systems (KBS) dates from the development of DENDRAL [4] for inferring chemical structures from mass-spectrometry data and MYCIN [46] 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 [23], and pragmatic design rules for knowledge engineering in the current fifth generation era [27]. The utilization of their massive VLSI production capability [15,22] for the support of KBS through Lisp [3] and Prolog [7] machines is the other major priority in the Japanese FGCS program [40].

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 its acquisition, breakthroughs in machine learning and inductive inference systems (IIS). Two breakthroughs in this area have been Lenat's AM learning mathematics by discovery [9] and Michalski's inductive inference of expert rules for plant disease diagnosis [38]. In the current fifth generation era machine learning has become a highly active research area still in its replication phase [37].

It is reasonable to 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 automomous activity systems (AAS). One may 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).

LAUNCHING A NEW GENERATION

The timing of computer generations is surprisingly regular and seems to relate to the underlying business cycle of capital equipment purchase, the Juglar cycle originally identified in the nineteenth century [30] and apparent as an eight year cycle through to the current times [33]. The peaks in the Juglar cycle correspond to our eight year boundaries from 1940 through 1980; the USA statistics show the 1964 peak as being in 1967 due to purchases to support the Viet Nam war but the next peak is in 1972 on target showing the dominating effect of world trade cycles rather than national events [50].

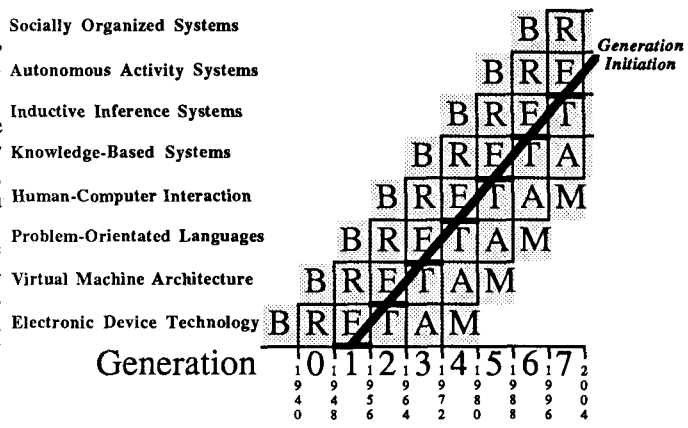

Figure 5 Generation Initiation Trajectory

It is interesting to link these cycles with Drucker's remarks comparing the development of the electricity industry with that of the information industry and making the analogy that "information is energy for mind work" [12]. 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." It was the invention of the light bulb that led to the use of electricity as a universal form of energy. It will be fifth and sixth generation developments in knowledge science and technology that will bring to fruition the new medium of computing [20,45] and launch an information age [11].

A generation of computers is a commercial entity, a development in product innovation. The relevant technology must have passed through its breakthrough and replication periods and be at a stage where empirical principles are being subsumed by theory. Figure 5 shows the line of generation initiation as one that passes through the ET junction in each generation. The junction in the fifth generation is between HCI and KBS corresponding to the FGCS emphasis on these topics and the launch of Prolog machines with powerful interactive intefaces and knowledge-processing capabilities. The junction in the sixth generation is between KBS and IIS corresponding to the SGCS emphasis on knowledge processing and acquisition, the foundations of knowledge science.

In the fourth generation the hardware and software technologies, EDT/VMA/POL, lie below the ET junction, and the human sciences technologies, HCI/KBS/IIS, lie above the junction. Hardware and software engineering had reached at least the theory stage in the fourth generation and the human sciences relating to the interface, knowledge processing and knowledge acquisition became the critical frontiers. Fifth and sixth generation developments depend on integrating knowledge from the human sciences with that from computer sciences.

CONCLUSIONS

The computer industry came into being as electronic device technology enabled the social need to cope with an increasingly complex world to be satisfied. 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 in succession 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. Each learning curve goes through a succession of phases: breakthrough; replication; empiricism; theory; automation; and maturity. The phases of the learning curves at each level in the infrastructure occur in eight

year generations corresponding to the business cycle of capital equipment purchasing. The FGCS program with its emphasis on HCI and AI, and the SGCS program with its emphasis on knowledge science are natural developments in the foci of attention indicated by the model.

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