From information to knowledge technology

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Information technology is in a process of transition from information processing to knowledge processing. Knowledge-based systems are already significant economically, and leading to major social change. We have to grasp new concepts of engineering knowledge, understanding its economics and dynamics, and processing it from raw materials to knowledge-based products. Information technology can best be understood as a phenomenon of the life world, generated by, and supporting its processes. Its manifestations in computing and genetic engineering are part of the search for complexity-reduction and improved anticipation of the future that motivates all human activity. Identifying the social needs underlying the generation of knowledge-based systems enables the requirements to be projected, and guesses made as to the forms of technology that will satisfy them, the types of society that will result, and the moral and ethical dilemmas that will have to be faced. This address reviews advances in artificial intelligence and robotics, and their impact on the engineering profession and social issues.

> *"Human knowledge and human power meet in one; for where the cause is not known the effect cannot be produced. Nature to be commanded must be obeyed; and that which in contemplation is as the cause is in operation as the rule."* (Bacon, 1620, Novum Organum)

1 Introduction—Knowledge Engineering—Knowledge Economy

Knowledge has always been significant to our civilization. However, in the past fifty years this significance has grown to a level where it is coming to dominate other socio-economic factors. Machlup in 1962 drew attention to the major and growing role of information services in the US economy and estimated that in 1958 knowledge production accounted for 29% of the US GNP. Porat's detailed analysis of the 1967 US national income-and-accounts estimated that the information sector accounted for 46% of GNP. Drucker took this up as a major issue in his 1968 book, *The Age of Discontinuity* and estimated that by 1975 the knowledge sector would account for 50% of US GNP. In the 1970s the predicted transition commenced to a post-industrial economy less dependent on manufacturing and human labour, and more dependent on knowledge and information technology.

More dramatic scenarios of the socio-economic consequences of the transition to a knowledge economy have been painted by Toffler in his 1980 book, *The Third Wave*, by Dizard in his 1982 book, *The Coming Information Age*. Bell has given an economic analysis of expected social change in his 1973 book, *The Coming of Post-Industrial Society*, and Wojciechowski has analyzed the increasing significance of the knowledge product to human society and emphasized the importance of understanding and managing the *knowledge ecology*. These global models of human civilization show our increasing dependence on the effective dissemination, use and extension of the store of knowledge. Our over-crowded planet with its diminishing resources can support the still-increasing human population only because we have the knowledge to make efficient use of available resources.

In the 1980s we have become acutely aware of being in an information age and the engineering professions are both major consumers of the new information technologies and major producers of innovative applications of knowledge-based systems. It is common to speak of *knowledge engineering* as the foundations of expert system development, and of the growth of the *knowledge economy*. Yet, as we apply familiar terminology to the new situation, are we really coming to terms with its novelty? Is “knowledge” a raw material that may be “mined, molded and assembled” as Hayes-Roth suggests. Does the “currency” of a knowledge economy have similar properties to previous financial instruments? If there is knowledge engineering then what is knowledge science and technology?

These questions are not easily answered. Yet, they cannot be treated as merely rhetorical. This paper suggests that knowledge-based systems will be the focus of advances in all engineering disciplines during the 1990s and into the next millennium. The control of information is the key technology underlying not only computing, communication and control but also genetic engineering and the space program. Knowledge technology is not the latest fashion, or example of autonomous technology run wild, but rather the culmination of socio-cultural developments at the heart of human existence, survival and evolution.

2 Steps into the Information Age

Figure 1 shows critical technological developments from 1947 through 1987. At the beginning of the 1960s the first generation of computing was barely complete with batch processing on large, expensive and unreliable machines. The transistor had been invented but was not in widespread use. The structure of DNA had been discovered but the genetic code was still unknown. The first spacecraft had just been launched.

During the second and third generations the increasing reliability and decreasing cost of computers made possible direct human-computer interaction. The invention of the silicon planar process gave birth to modern microelectronics and integrated circuits. The genetic code was cracked and an artificial gene fabricated. Man entered space and walked on the moon.

During the fourth and fifth generations personal computers became consumer products, and progress in artificial intelligence enabled human knowledge to be encoded in expert systems. Very-large-scale integration reached the stage where in 1987 chips with 16 million bits have been constructed. Genetic engineering is being used to change the structure of living systems, plants and animal cells. The shuttle has reduced the costs of activity in space. Space stations will make prolonged operation possible, and many of the planets have been explored by unmanned probes.

Generation	Year	Event
	1947	Stored program digital computer
1	1948	Germanium transistor
	1953	Double-helix model of DNA
	1953	IBM's first computers
2	1959	Silicon planar transistor (1 on chip)
	1959	Luna spacecraft
	1960	Remote robot hand, Laser
	1961	Manned orbits
	1962	Communications satellite
	1963	Interactive computing (20 on a chip)
3	1965	Space walk and rendezvous
	1966	Genetic code fully decoded
	1970	Artificial gene
	1971	Lunar landing
	1971	Computer on a chip (5,000 on chip)
4	1972	Expert systems, Laser video disc
	1973	Space station
	1974	Genetic engineering
	1975	Personal computers
	1977	Space shuttle
	1979	Saturn probe (500,000 on chip)
5	1980	Six month manned orbit
	1980	Genetic engineering human trials
	1981	Fifth generation computer program
	1985	Encyclopaedia on optical disk
	1985	Sixth Generation computer program
	1987	(20,000,000 on chip)

Figure 1 Some significant technological events split up by generations of computers

3 Information Technology and Society

Our world is changing at a dramatic pace, but where is it going? Technological forecasting provides no answer to this question. Our civilization is not driven by a cause-effect chain based on the technologies available to it. Those technologies are the by-products of the processes of society, the teleological processes of a living system driven by its survival. To anticipate our socio-economic future we have to come to understand those processes—our own nature. The primary drive of a living system is its survival. To survive, the system must have access to the necessary resources and be capable of coping with threats to its survival. Systems evolve to maximize their access to resources and minimize their vulnerability to threats.

If the universe were static a simple model of resource availability and prey-predator relations would determine the dynamics of living systems. Until the advent of the human race this planet was a static universe over long periods of evolutionary time. The beginnings of the human race were set in this static universe but our activities soon began to change that universe so that uncertainty about the future became the predominant factor in our survival processes. Changes in the earth that would have taken millions of years began to occur over millennia. Now multiple waves of change occur within our lifetimes. We developed resources far beyond their natural availability and, in so doing, changed the ecology of the earth. We extinguished all predators other than ourselves and again changed the face of the earth. Much of this planet is now a human construct and the distinction between natural and artificial is increasingly becoming meaningless.

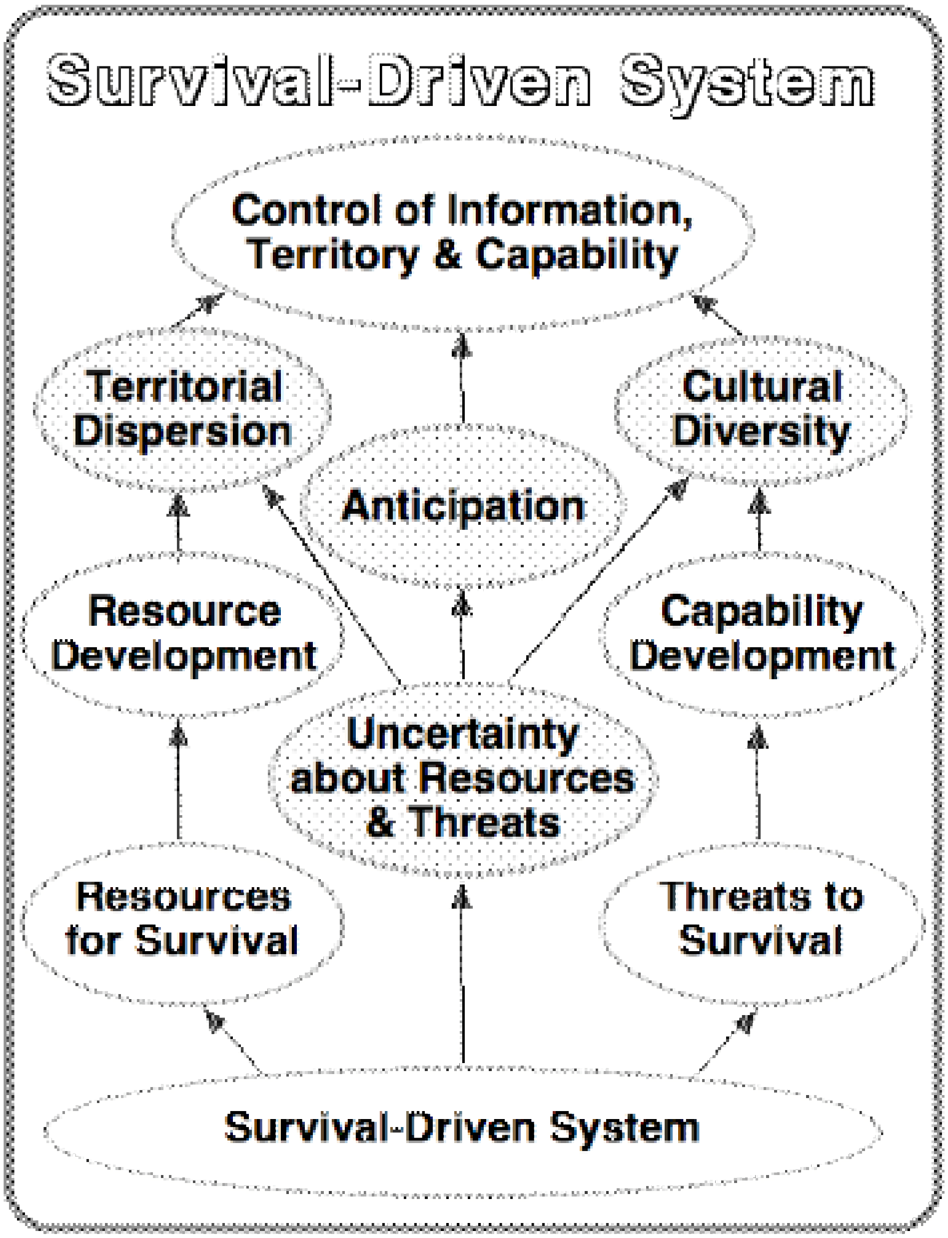

Figure 2 The system dynamics of human survival

Figure 2 shows the system dynamics underlying humanity. The shaded areas show the response to uncertainty. The keys to survival in an uncertain world are three-fold: first to maximize territorial dispersion so that some part of the system is outside the range of a threat; second to maximize cultural diversity so that some part of the system has the capability to survive a threat; third to improve anticipation of the future, passively to predict threats in advance, and actively to rebuild the universe so that they do not occur—those are the roles of science and technology. This is the logic of our present foci of attention: *information technology* for improved anticipation, the *space program* for improved territorial dispersion, and *genetic engineering* for improved cultural diversity.

3 The Control of Information

What are the implications of our transition to a changing and uncertain man-made world? The major implication is that which leads to the notion of a knowledge-based economy. Knowledge itself has become our fundamental resource. As Wojciechowski has noted, it is human knowledge that has created the world we live in, including its problems, and it is human knowledge that provides the only available solutions. The husbanding, harvesting, and management of knowledge—what he terms the *ecology* of knowledge—is as important today as the ecology of the physical environment has ever been.

Knowledge is unitary—the boundaries between materials, processes, devices and systems, or between physics, chemistry and biology, are becoming meaningless. Too rigid adherence to such distinctions is an impediment to effective operation in a knowledge-based economy. Disciplinary boundaries have been the scaffolding that enabled us to construct a vast edifice of knowledge piece by piece before we had the capabilities to encompass it as a whole. Information technology has been developed to hold together the edifice without the scaffolding. The encyclopaedia on a small optical disk and the expert systems of today are the precursors of the total integrated *knowledge support systems* of tomorrow.

We know that information technology underlies computing systems. However, in a wider sense it also underlies genetic engineering. Microelectronic device fabrication is the control of information structuring semiconductor devices at the molecular level. Genetic engineering is the control of information structuring living organisms at the molecular level. These apparently very different technologies have common roots, dependencies and potential as shown in Figure 3, and there will be increasing interaction between them.

At the macro level the socio-economic processes of a knowledge-based economy are information-driven and the key to prosperity and the quality of life in such an economy is the effective control and application of information. In manufacturing, it is the flow of information that structures the operation of a modern factory. The drive towards total automation through robotics and computer-integration is critically dependent on the development of manufacturing automation protocols to control the flow of that information. In banking it is the flow of information that determines the availability of funds rather than the movement of actual financial instruments.

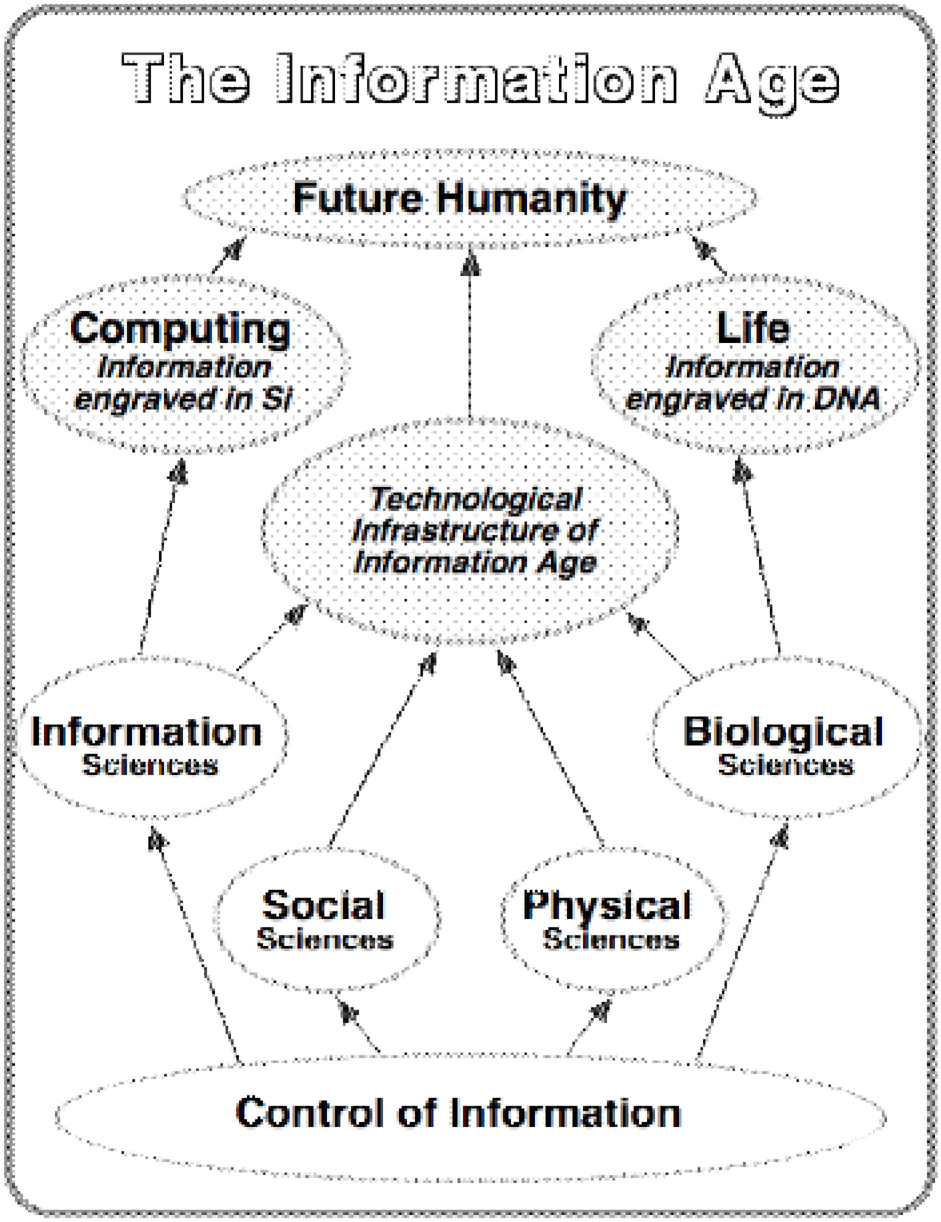

Figure 3 The control of information

The power of information control systems is nowhere more apparent than in the diversity of activities possible at a computer terminal. Someone working at a terminal, with the same computer, display and much common software, may be designing: a computer program to calculate a payroll; an expert system for advising managers; a complex metal piece part; a microelectronic device; a chemical catalytic process; a genetic structure; and so on. What is even more remarkable is that the results of their design can be implemented without further human intervention—the metal piece part may be turned and milled by numerically-controlled machine tools and placed in position by robot arms—the catalytic process may be simulated and then used with no empirical laboratory testing.

Figure 4 shows the space program as associated with the survival processes of territorial dispersion, and supported by information technologies.

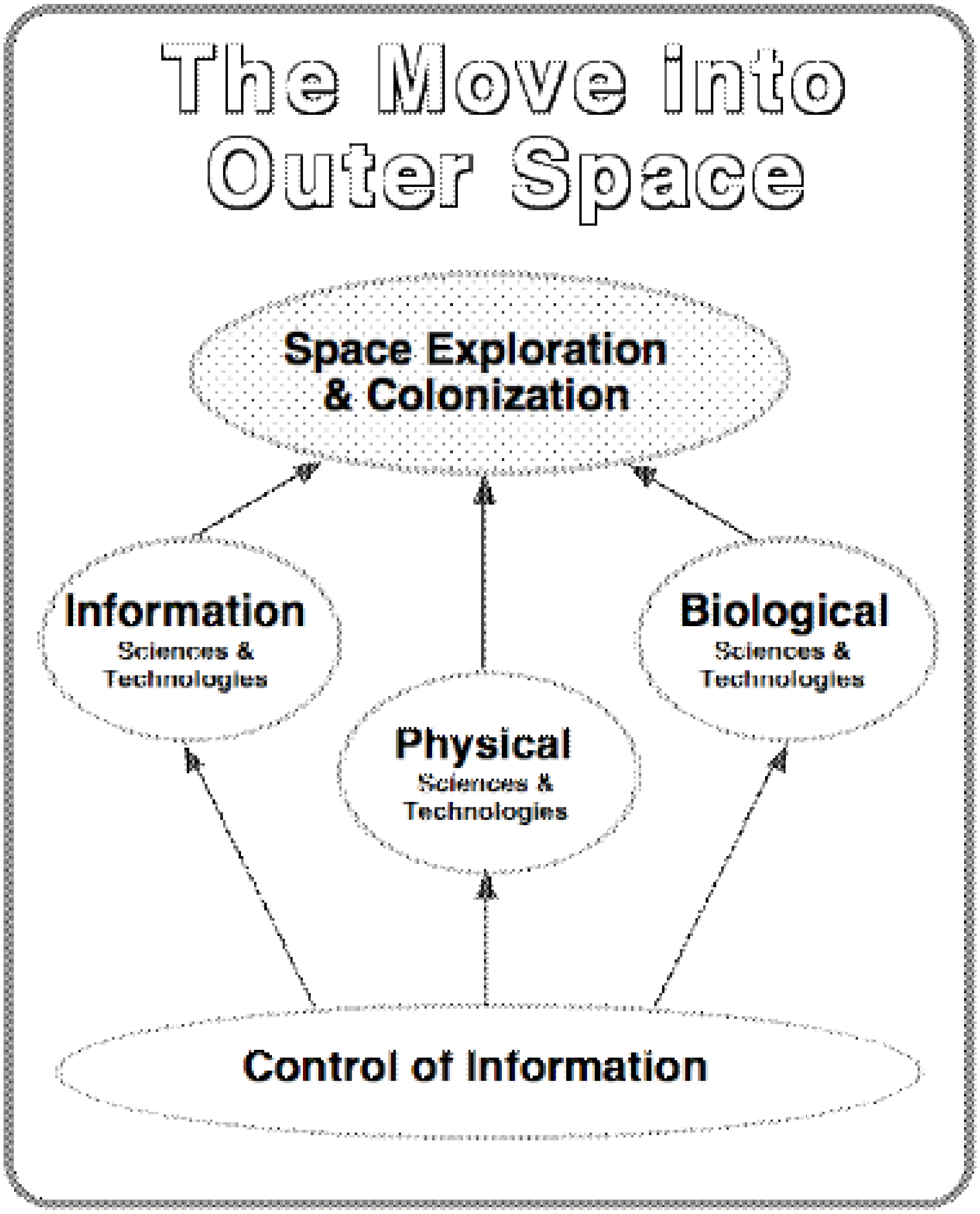

Figure 4 The move into outer space

Figure 5 shows how this move into outer space is being paralleled by equally significant moves into inner space, the development of human potential consistent with the survival processes of cultural diversity. Genetic engineering will enable us to make direct changes in the species, allowing us to take direct, short-term control of biological processes whose evolution would otherwise be erratic over millennia. However, physical change in the species is only one source of potential for major restructuring of humanity. Mental change through greater understanding of our own cognitive processes is also significant.

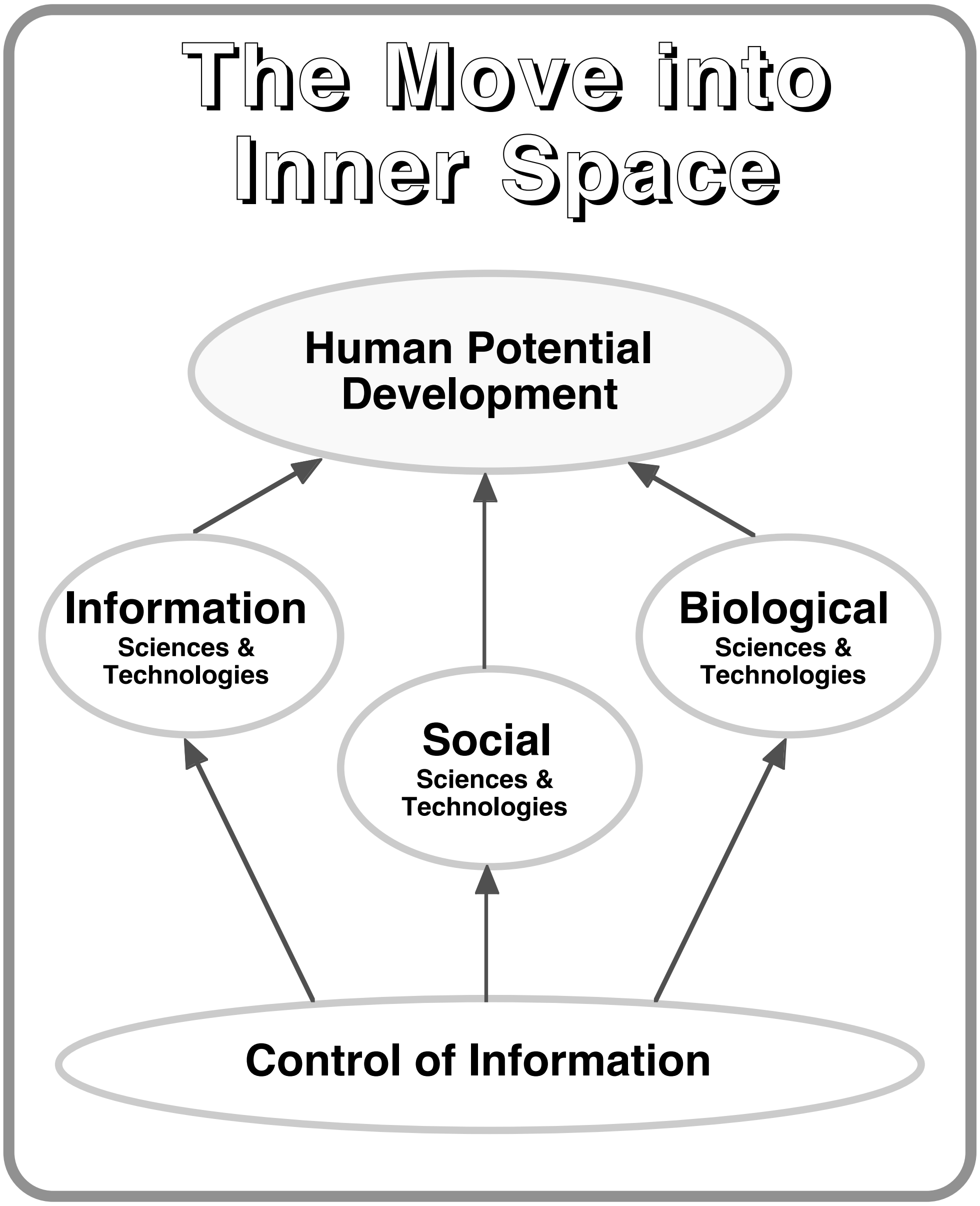

Figure 5 The move into inner space

Advances in knowledge science are already making such indirect changes. Research on rapid prototyping for expert systems is analyzing the knowledge transfer processes of humanity and will change the foundations of our educational system, our understanding of ourselves, and eventually our culture and modes of being. Research on the nature of knowledge itself, as an autonomous system existing in its own right with a status similar to that of the physical world, is leading to new understanding of the nature and role of humanity.

4 The Role of Knowledge-Based Technologies

The high-technology applications of knowledge-based systems naturally attract much attention. However, the long-term socio-economic significance of frontier technology should not divert attention from the immediate applications of knowledge-based systems. The *pre-industrial* and *industrial* sectors of Bell's economic model as shown in Figure 6 are still basic to human existence.The shift of labor from these sectors in *post-industrial* society is dependent on the application of information technology.

Figure 7 shows his 1973 projection of the critical factors underlying modern society, and in the 1980s the new "intellectual technology" of knowledge-based systems has come into being.

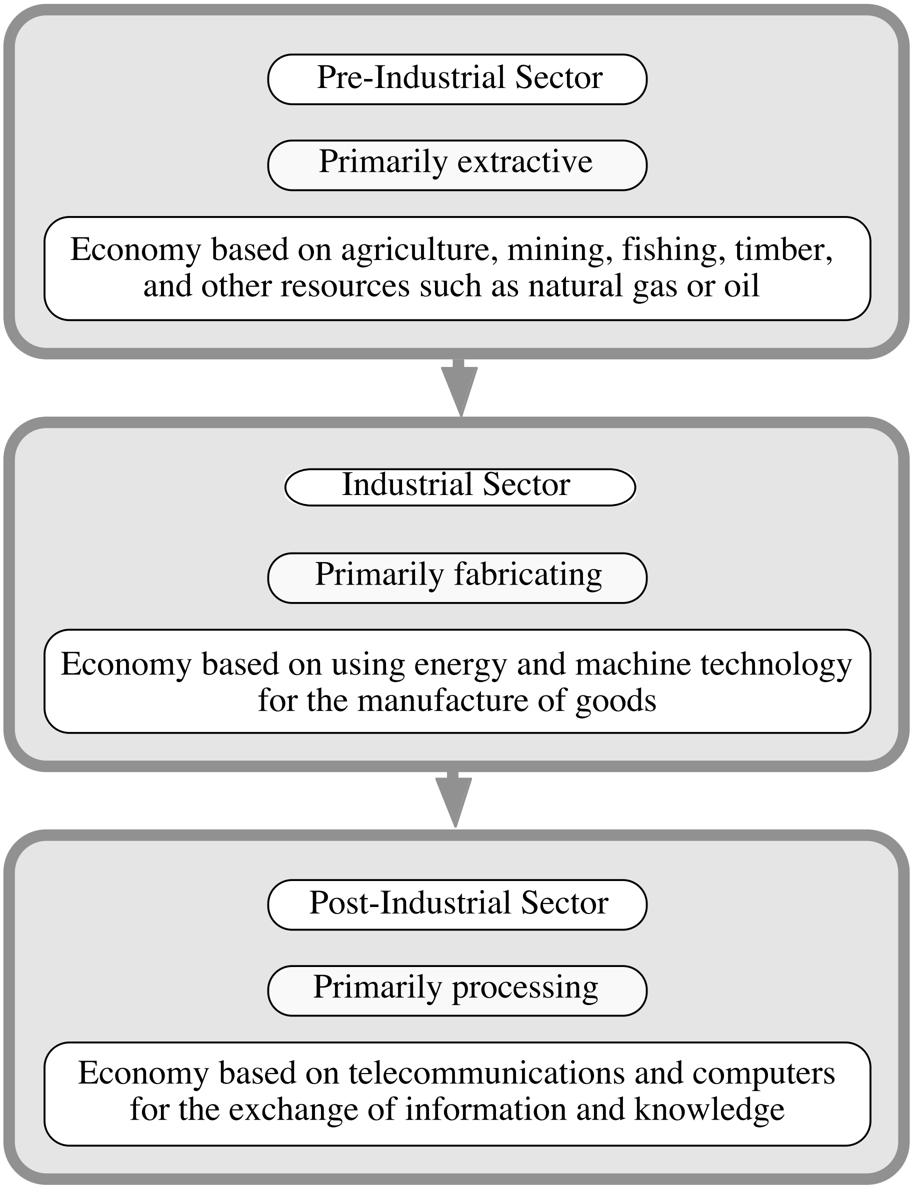

Figure 6 Economic sectors

Economic Sector	Change from a goods producing to a service economy
Occupational Distribution	Pre-eminence of the professional and technical class
Axial Principle	Centrality of theoretical knowledge as the source of innovation and policy formulation for the society
Future Orientation	Control of technology and technological assessment
Decision-Making	Creation of a new "intellectual technology"

Figure 7 The post-industrial sector

Figure 8 shows how the new technology impacts each of the three economic sectors. In the past the pre-industrial and industrial sectors have had a mutual exchange relationship in which the pre-industrial provides materials for the industrial, and the industrial provides equipment for the pre-industrial. Now the industrial also provides equipment for the post-industrial, and the post-industrial provides knowledge-based systems for both the pre-industrial and the industrial—expert systems for resource exploration and development and for energy-efficient farming—computer-integrated manufacturing for low-cost, automated flexible industries.

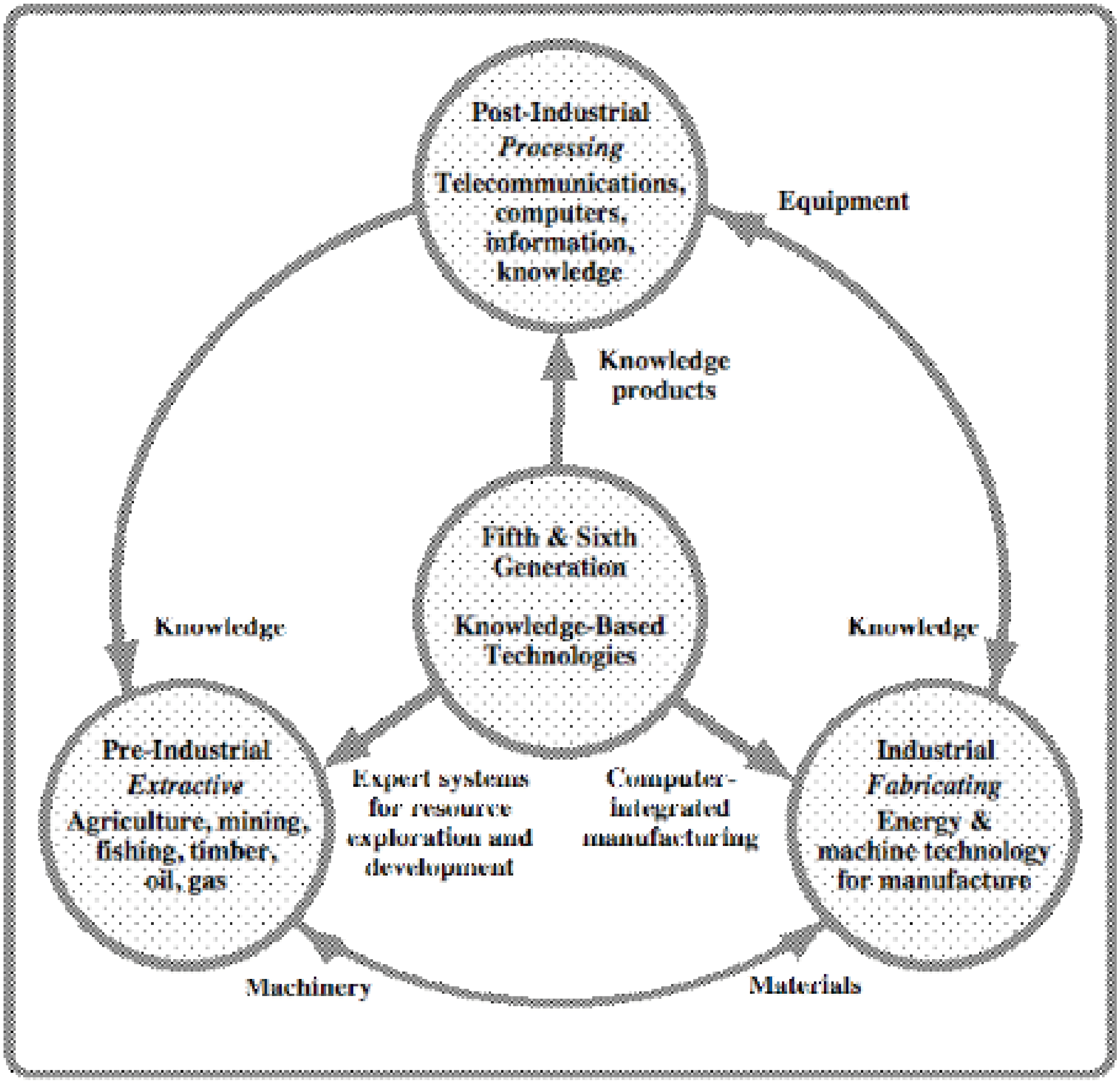

Figure 8 Relations between sectors

The most important applications of the new knowledge-based technologies in the short term are to the older industries at the base of our economy—no engineer can afford to neglect them.

5 The Infrastructure of Information Technology

In coming to understand information technology, it is important to realize the computer itself is only one component in an elaborate and highly differentiated infrastructure. At the base of this infrastructure is electronic device technology. In 1956 the silicon planar transistor was invented and enabled integrated circuit technology to be developed. Figure 9 shows the exponential growth of the number of devices on a chip:

- 20 in 1964 allowed the first flip-flop to be integrated;
- 5,000 in 1972 allowed the first 1 Kilobit ram (Intel 1103) and microcomputer (Intel 4004) to be integrated;

- 500,000 in 1980 allowed major central processing units to be integrated;
- 16,000,000 in 1987 is leading to 16 Megabit rams.

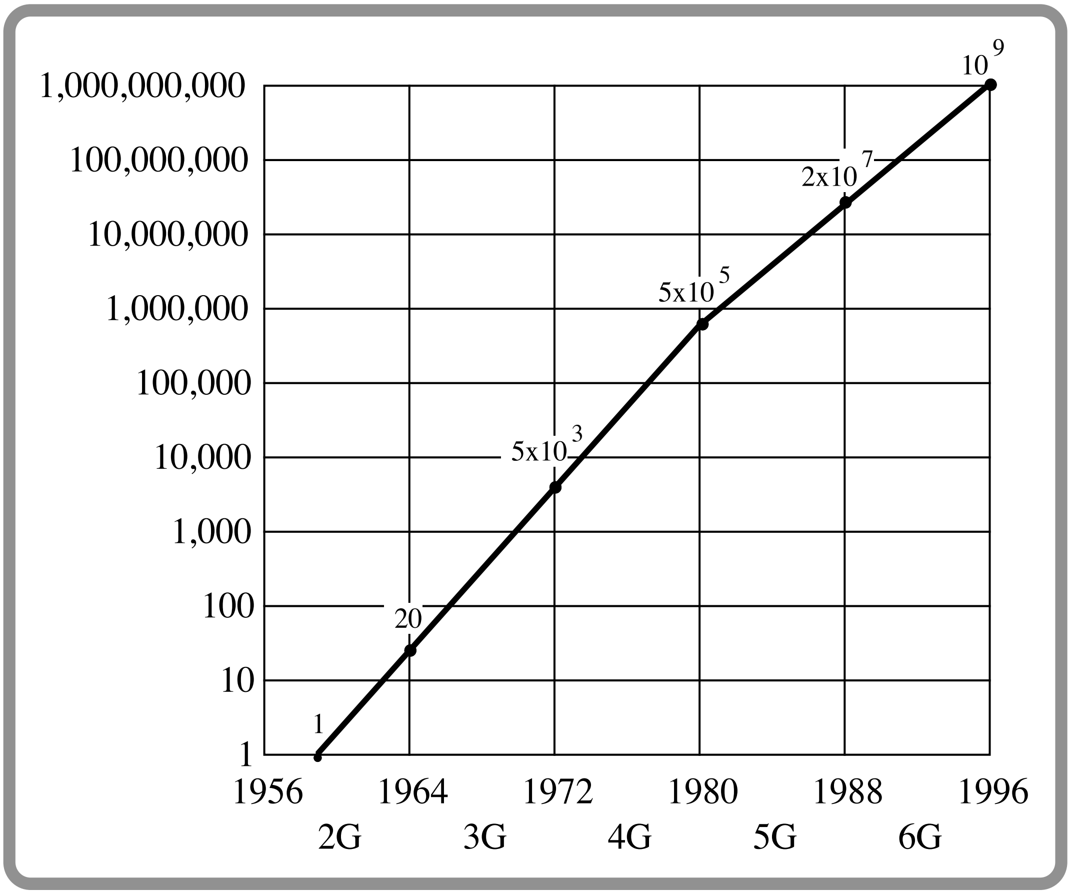

Figure 9 Number of devices on a chip

The exponential growth will continue through 1000,000,000 million devices on a chip in the late 1990s when quantum mechanical effects will become a barrier to further packing density on silicon planar chips. Three-dimensional packing, semiconducting peptides, optical devices, or, most likely, new materials not yet considered, will extend the growth shown in Figure 9.

However, Figure 9 is misleading because it shows a continuous progression on an exponential plot over 9 decades of performance increase. Such progression is common in many technologies, but never over more than two decades and then in periods of the order of 100 years rather than 10. Computer technology is unique in being based on underlying devices whose performance has increased at a rate and over a range achieved by no other technology.

The distortion caused by the logarithmic plot is apparent in the linear plot of the same figures in Figure 10. Now nothing appears to happen until 1980 when the technology suddenly shoots off. However, this is what has happened in every generation of computers as shown in Figure 11 where the exponential plot in each generation is rescaled to appear on the same vertical axis. There has been a revolutionary change in the base technology in every generation of computers.

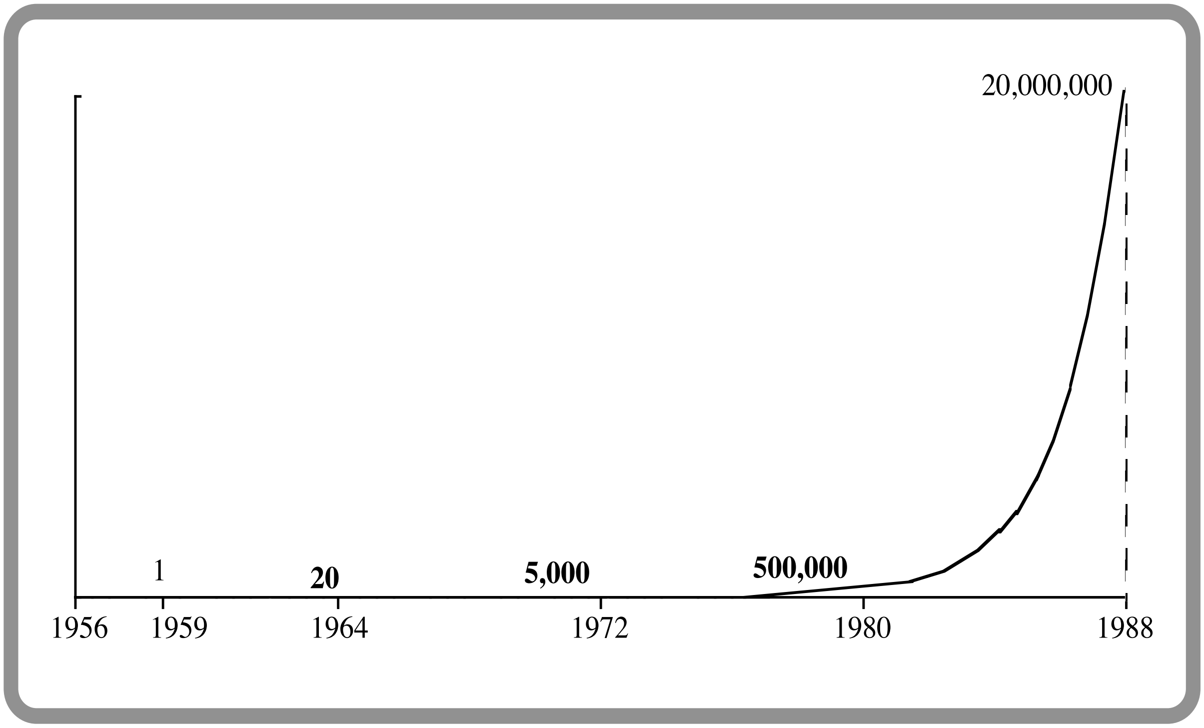

Figure 10 Linear plot: devices on a chip

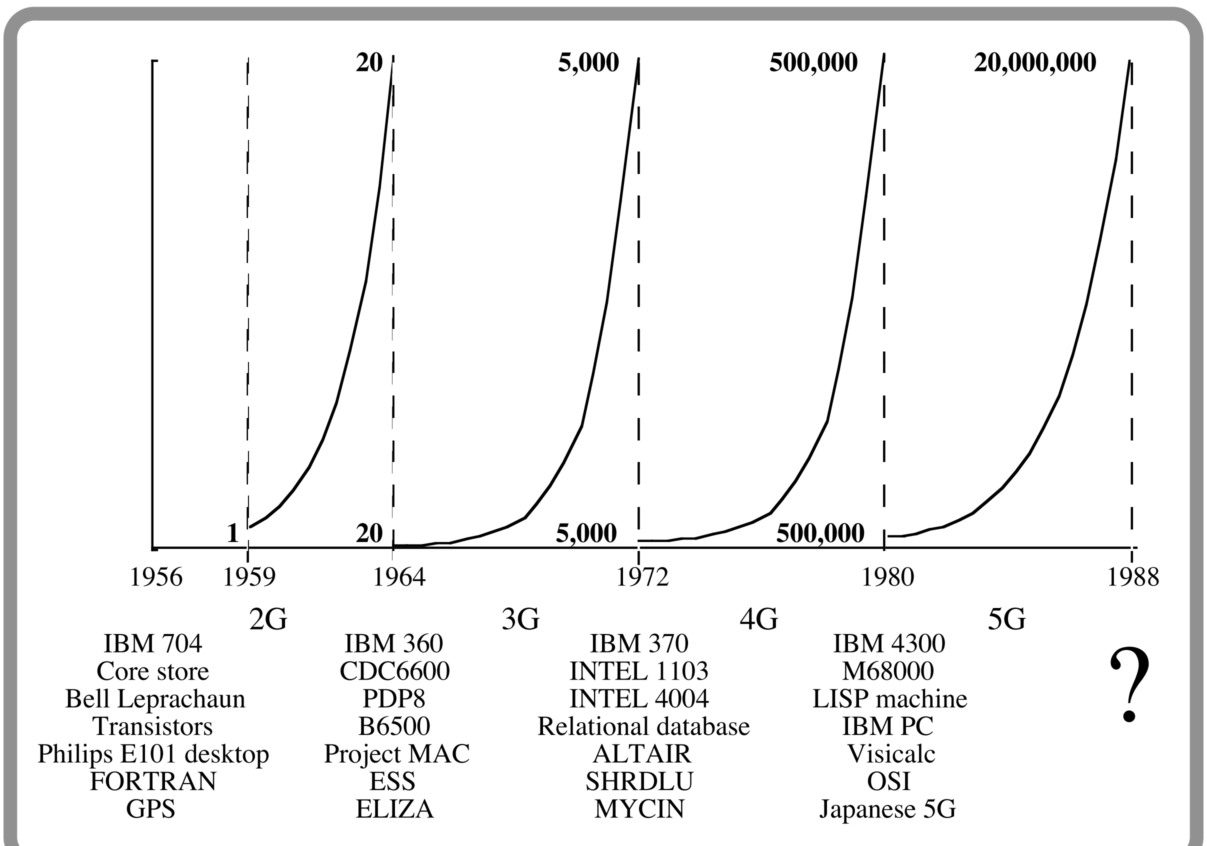

Figure 11 Devices on a chip in each generation

The massive quantitative changes in electronic technology have been reflected as major qualitative changes in the applications of that technology, sufficient to be regarded as new technologies in their own right. Figure 12 shows the tiered infrastructure of information technology as a series of technology developments, each triggered off by major changes in the technology below, and each following the basic technological learning curve of:

- *breakthrough*, in which a creative advance is made generally after many failures; *replication*, in which the advance is mimicked widely in various research groups;
- *empiricism*, in which design rules gained from experience are used to guide development;
- *theory*, in which the design rules have become so cumbersome and the experience has become so broad that technological models can be developed;
- *automation*, in which the theoretical models are made operational;
- *maturity*, in which effort focuses on cost reduction and quality improvement.

In these terms:

- the initial zeroth generation breakthrough was in *electronic device technology* was in 1940 at the time of the Atanasoff and Berry experiments with tube-based digital calculations;
- 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*;
- the second generation breakthrough was to bridge the gap between machine and task through the development of *problem-orientated languages* such as FORTRAN around 1956;
- the third generation breakthrough was to bridge the gap between computers and people with the development of interactive time-shared computers in 1964 allowing *human-computer interaction*;
- the fourth generation breakthrough was in the early 1970s with developments in expert systems based on knowledge-processing—such *knowledge-based systems* have the capability to store information through its inter-relations and make inferences about its consequence;
- the fifth generation breakthrough was in 1980 with developments in machine learning and *inductive inference systems*;
- 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*;
- the interaction between these systems will become increasingly important in enabling them to cooperate to achieve goals—the seventh generation era commencing in 1996 will be one of *socially organized systems*.

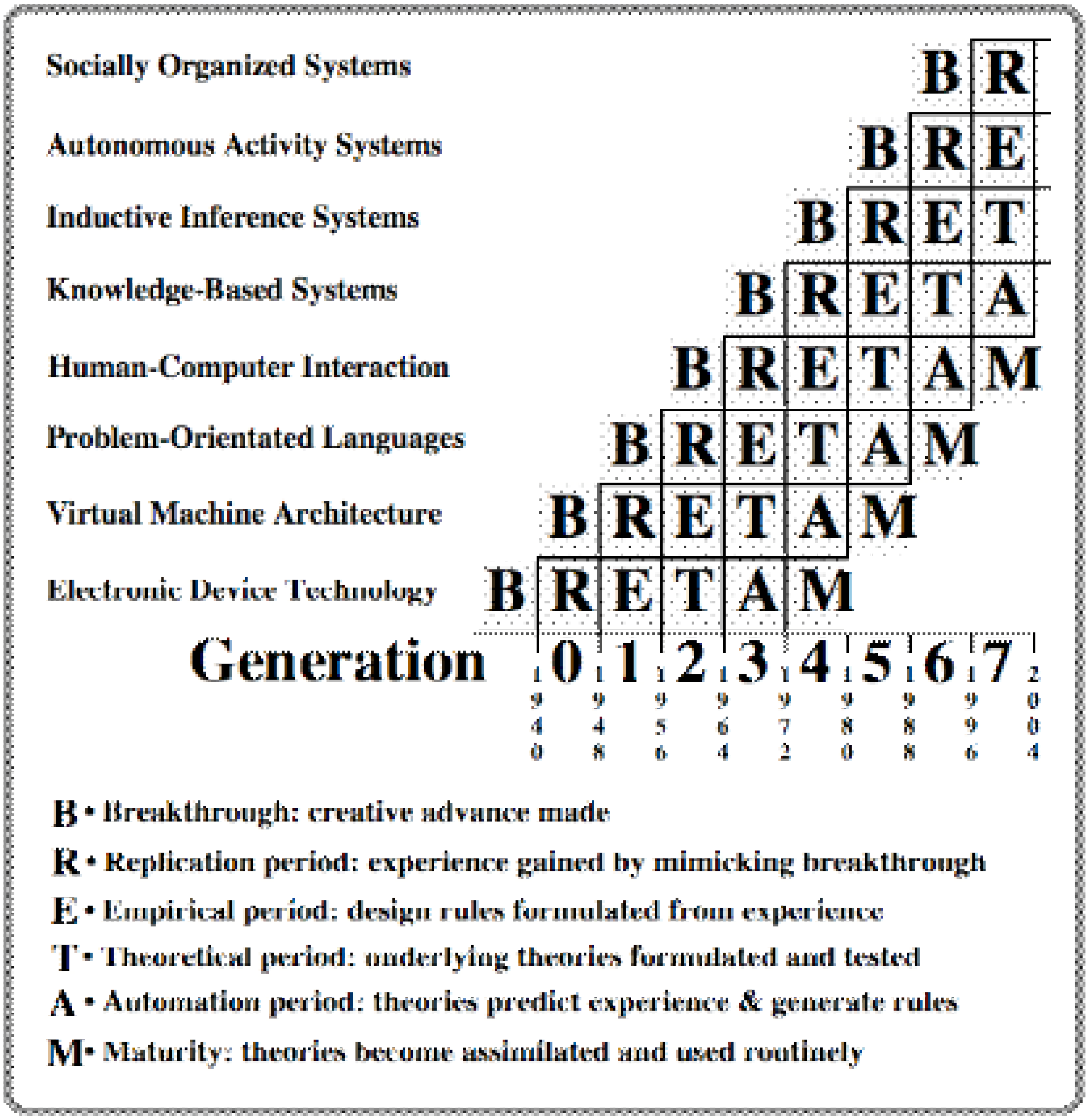

Figure 12 The infrastructure of information technology

6 Invention, Research, Innovation and Products

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 as shown in Figure 13.

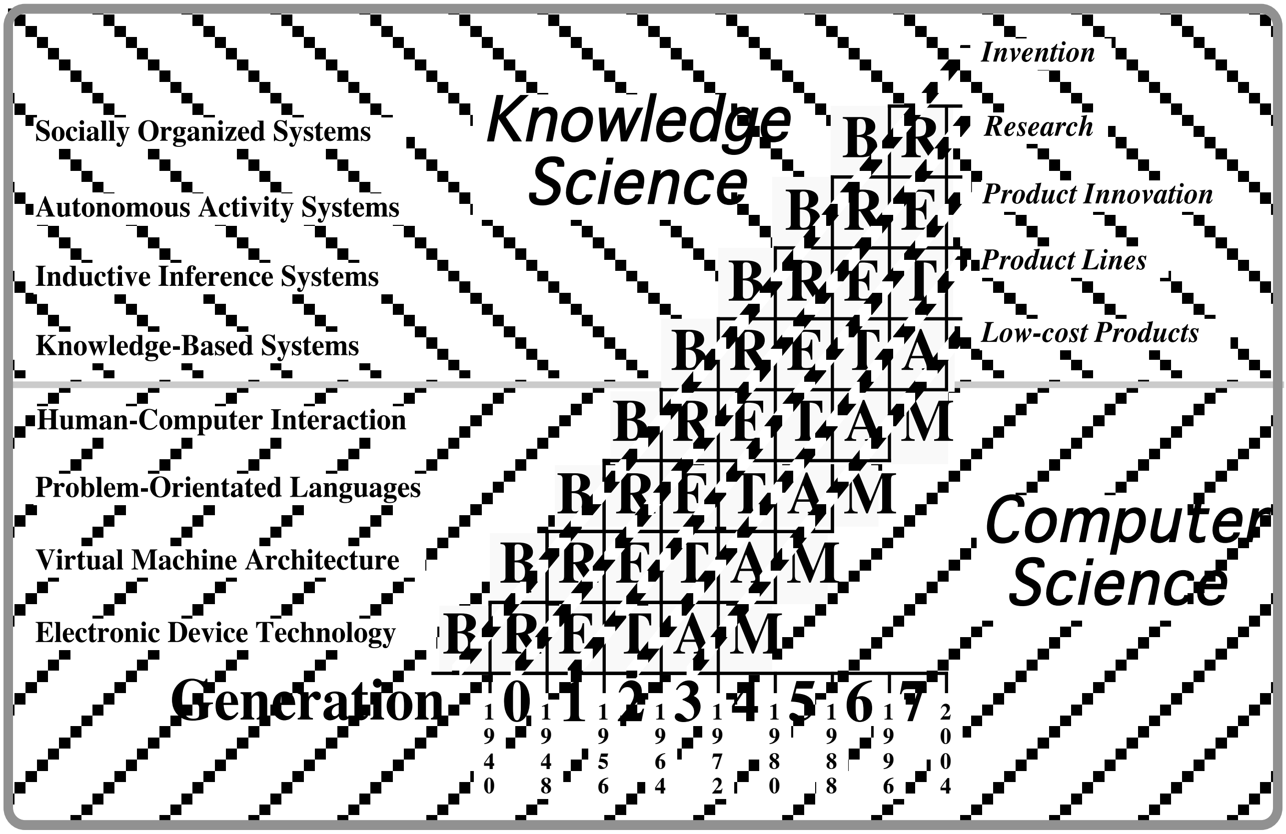

Figure 13 Invention, research, innovation and products through the generations

Figure 13 shows that:

- *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 technologies 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 those below;
- *Product Lines* are focused at the TA interface where product lines can rest on the solid theoretical foundations of one technology and the automation of the technologies below;
- *Low-cost Products* are focused at the AM interface where cost reduction can be based on the the automated mass production of one technology and the mature technologies below.

For example, in the fourth generation (1972-79):

- BR: recognition of the knowledge acquisition possibilities of knowledge-based systems led to the breakthrough to inductive-inference systems;
- RE: research focused on the natural representation of knowledge through the development of human-computer interaction, e.g. the Xerox Star direct manipulation of objects;
- ET: experience with the human-computer interaction using the problem-oriented language BASIC led to the innovative product of the Apple II personal computer;

- TA: the simplicity of the problem-oriented language RPG II led to the design of the IBM System/3 product line of small business computers;
- AM: special-purpose chips allowed the mass-production of low-cost, high-quality calculators.

In the current fifth generation (1980-87):

- BR: recognition of the goal-seeking possibilities of inductive inference systems is leading to the breakthrough to autonomous-activity systems in robotics;
- RE: research is focused on learning in knowledge-based systems;
- ET: the advantages of the non-procedural representation of knowledge for human-computer interaction led to the innovative designs of the Visicalc spread-sheet business product and the Lisp-machine scientific product;
- TA: the ease of human-computer interaction through a direct manipulation problem-oriented language led to the Apple Lisa/Macintosh product line of personal computers;
- AM: the design of highly-integrated language systems has allowed the mass-production of low-cost, high-quality software such as Turbo Pascal.

This model is very important in understanding the impact of information technology on other industries. The line of *product innovation* marks the practical availability of the various stages of new technology, and it lags the line of *invention* by 16 years, and in its turn is lagged by the line of *low-cost products* by 16 years. Thus there is a 16 year gap between invention and significant application, and a 32 year gap between invention and mass-production. Figure 14 shows the model applied to data processing technologies:

- in the first generation, *experimental hardware* and *machine code* programming were inadequate for data processing;
- in the second generation, *batch processing* overcame the continuing unreliability of the hardware and made the data processing industry possible;
- in the third generation, *high-level languages* made effective *management information systems* possible;
- in the fourth generation, *interactive access* made effective *decision support systems* possible;
- in the current fifth generation, *expert systems* are making *advisory aids* to decision making feasible;
- in the coming sixth generation, *machine learning* will make *adaptive, self-optimizing* management systems possible;
- in the future seventh generation, *machine autonomy* will make automated *goal-directed* management systems possible.

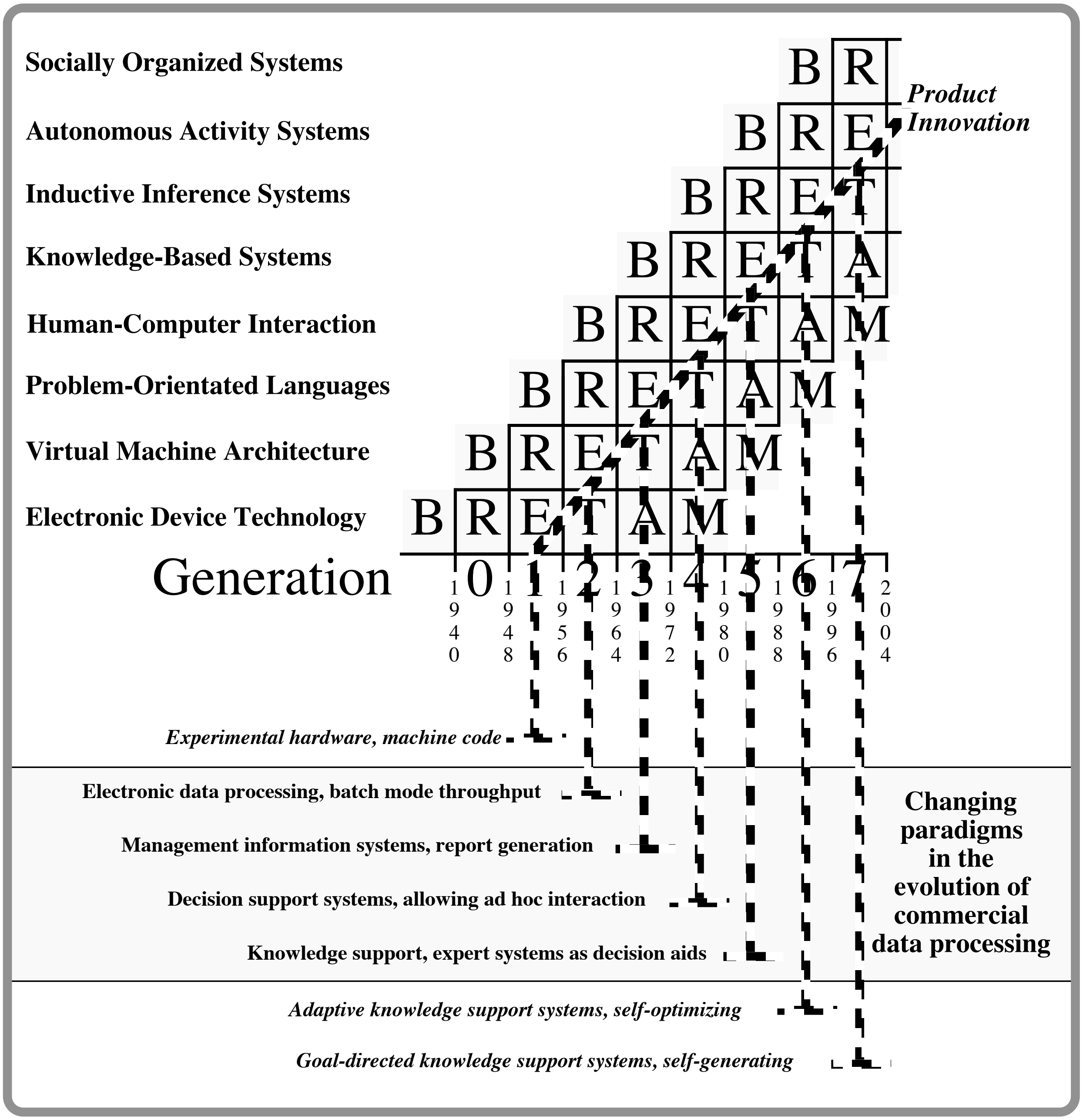

Figure 14 Changing technologies in data processing

Similar analyses are feasible for any sector, industry or project where information technology may be applied. The time of application determines the position along their learning curves of the various technologies underlying information technology, and this in turn determines what is feasible in applications. The learning curve model of Figures 12 through 14 is also significant for a company or country attempting to get into a new technology. It is not appropriate to commence research and development when a technology is already mature—it is then better to buy into existing industry.

7 National Programs for Information Technology

The breakthrough from computer science to knowledge science in the 1980s prompted a number of major national research programs. The trigger for these was Moto-okas's 1982 announcement of the Japanese Fifth Generation Computing System development program. Figure 15 shows his concept of the research objective: computing systems that took the best of fourth generation technology and extended it with techniques of artificial intelligence and advanced human-computer interaction. An integration of high-speed, vlsi hardware with knowledge-based software aimed at intelligent systems and improved human-computer interfaces.

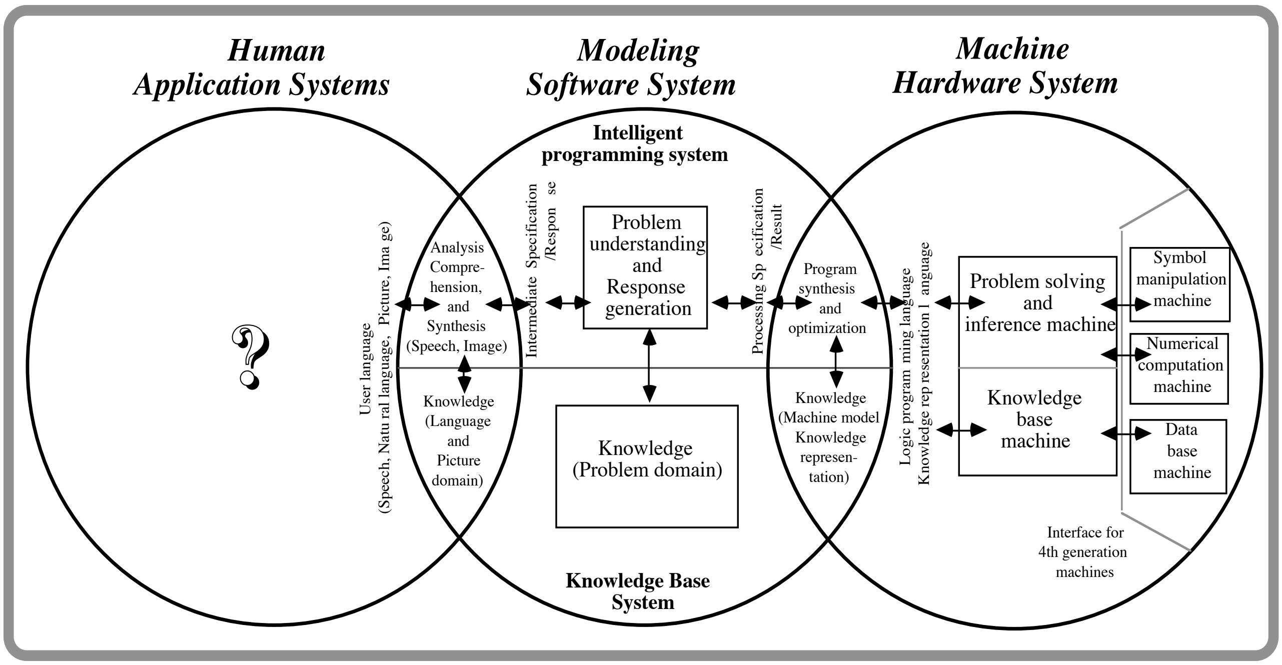

Figure 15 Japan's ICOT's "Conceptual diagram" of fifth generation objectives

Figure 16 lists the ambitious computing research program which Moto-oka originally proposed. It was targeted on significant applications and involved basic research on knowledge-based intelligent software, a range of innovative computer architectures, distribution of function, and application to a range of problems, emphasizing human-computer interaction, including machine translation.

However, the Japanese fifth generation research at ICOT has concentrated on machine architectures for knowledge-based systems based on high speed Prolog and relational database machines and involves no direct research on artificial intelligence or human-computer interaction.

The market-driven, and socially responsive, program put forward in the original fifth generation proposals has been implemented very much as a technology led activity. It is best seen as a program of system integration rather than fundamental research.

Basic Application Systems	Machine translation system Question answering system Applied speech understanding system Applied picture & image understandng system Applied problem solving system
Basic Software Systems	Knowledge base management system Problem solving & inference system Intelligent interface system
New Advanced Architecture	Logic programming system Functional machine Relational algebra machine Abstract data type support machine Data flow machine Innovative Von Neumann machine
Distributed Function Architecture	Distributed function architecture Network architecture Data base machine High-speed numerical computation machine High-level man-machine communication system
VLSI Technology	VLSI architecture Intelligent VLSI-CAD system
System Integration	Intelligent programming system Knowledge base design system System integration for computer architecture Data bases and distributed data base systems
Support System	Development support systems

Figure 16 Japanese fifth generation proposal

Moto-oka's visionary research program has come about, however, in that the Japanese initiative stimulated competing programs in the USA and Europe. These, with some fifty times the funding of ICOT and access to a much larger pool of experienced computing researchers, have largely achieved the fifth generation objectives. The Japanese protagonists of fifth generation development have protested that they hoped for international collaboration rather than competition. However, with the widespread dissemination of information technology research through journals and conferences, there is intrinsic collaboration—scientific and technological advance is now essentially international.

The DARPA Strategic Computing program in the USA naturally has overt military objectives although the bulk of the activities are basic information technology research as shown in Figure 17, most of which was already underway prior to the Japanese announcement. The technical balance is similar to that of Figure 16 but the applications targeted differ and the level of funding is an order of magnitude higher.

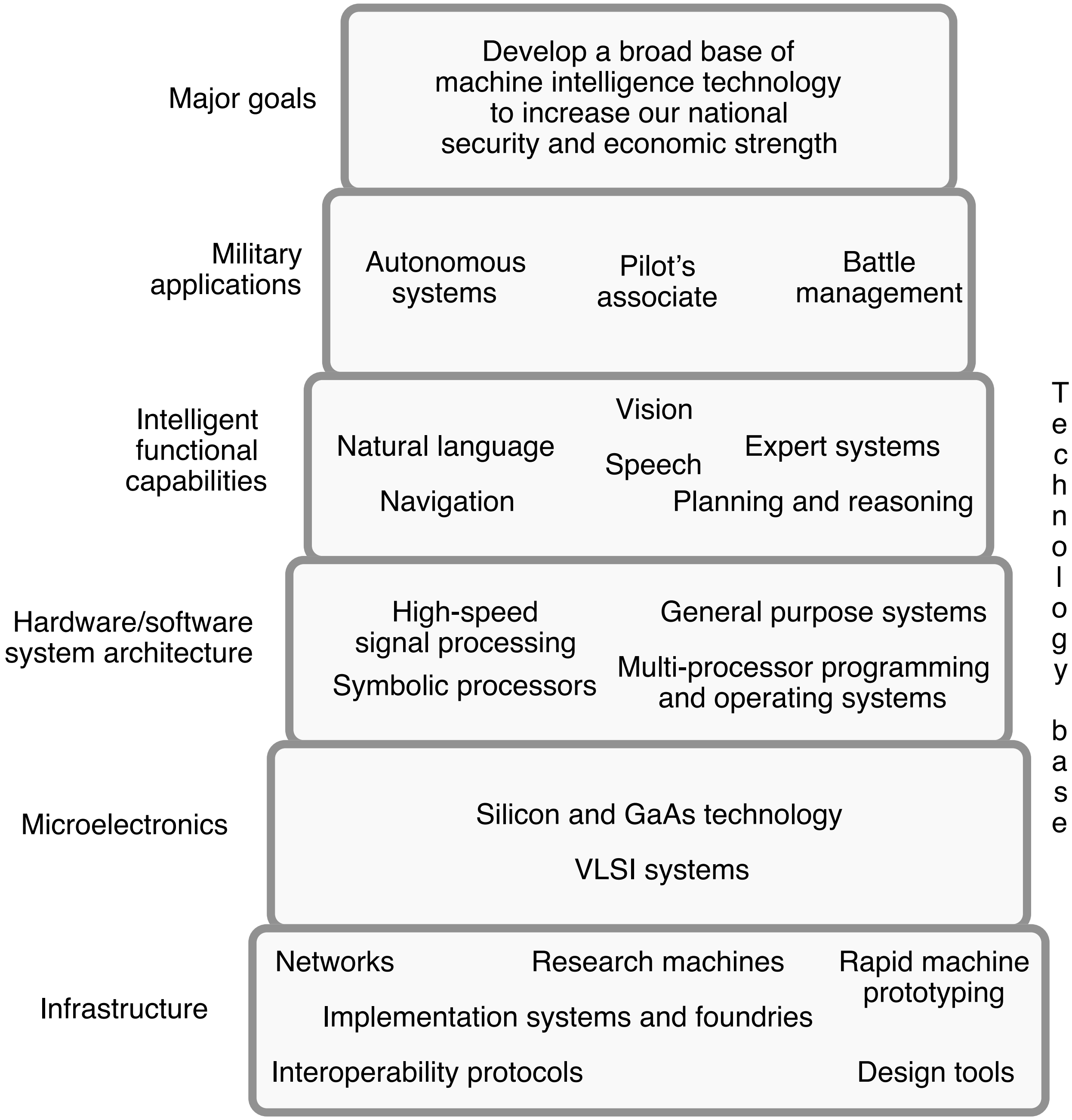

Figure 17 US military—DARPA Strategic Computing Program

The new initiative in the USA was the formation of the Microelectronics and Computing Technology Corporation (MCC) under Admiral Inman at Austin involving most major US computer companies. This involved changes in US anti-trust laws enabling such cooperative research ventures which will have far-reaching consequences. The MCC program structure is shown in Figure 18 and parallels the Japanese proposals of Figure 16.

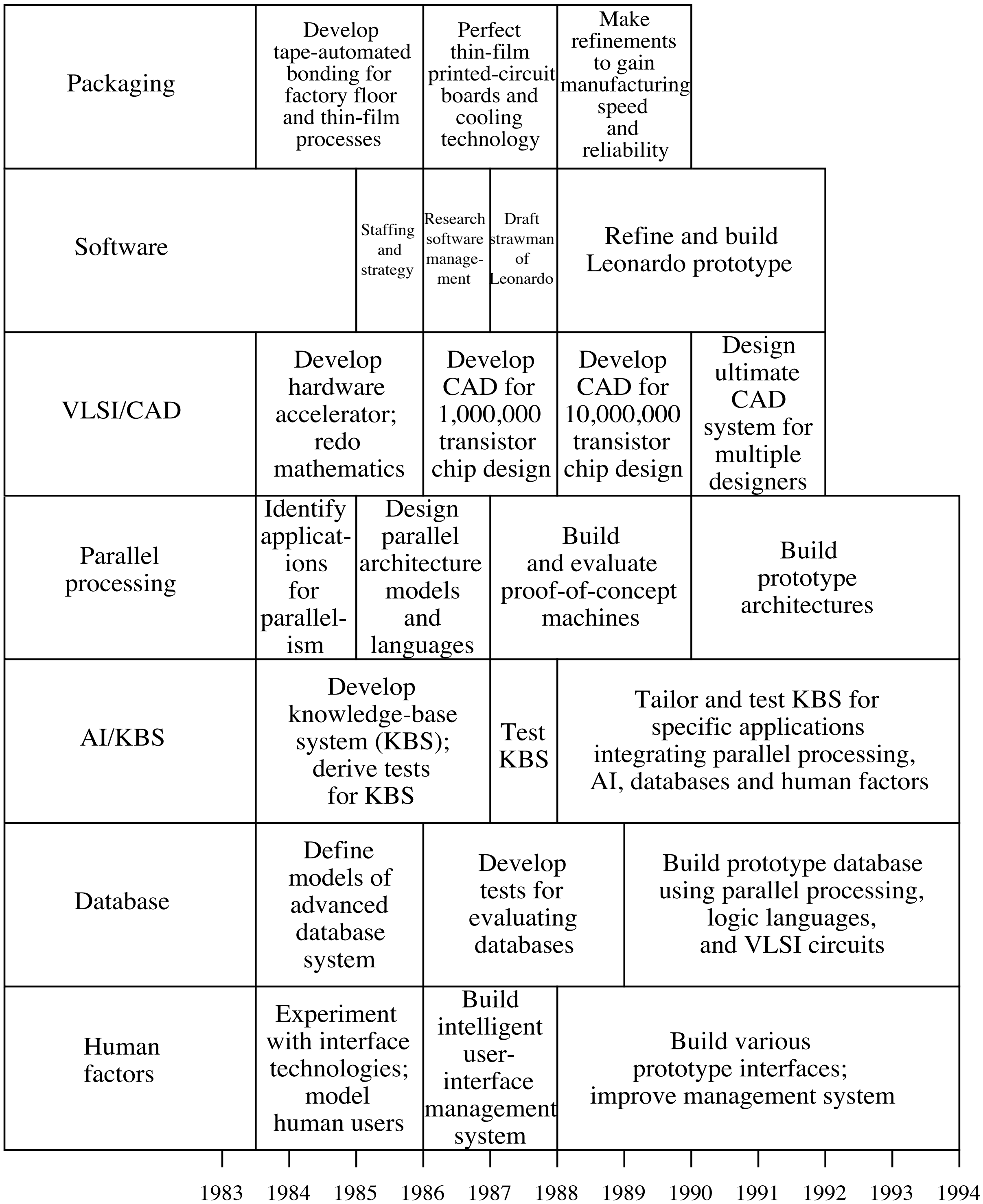

Figure 18 US industrial—MCC cooperative computing program

Even more remarkable has been the European response through its ESPRIT cooperative research program linking high-technology companies and universities across many European Economic Community countries. The language and cultural barriers in Europe have made such cooperation rare in the past, and ESPRIT has launched trans-national computing research on a scale which will change the nature of high-technology research in Europe. Figure 19 shows the ESPRIT program structure, and it is interesting to note the additional applications focus on office systems and computer-integrated manufacture, both major applications for fifth generation developments.

Advanced Micro-Electronics	24 projects including • CAD for VLSI system, European CAD integration • VLSI design workstation, Knowledge-based design assistant • GaAs-GaAlAs integrated circuits, InP optoelectronics • Optical interconnection, Liquid crystal displays • Wafer scale integration, 0.5 micron X-ray lithography • Submicron contacts, Polymers for multilayer interconnection
Software Technology	16 projects including • Formal methods for asynchronous systems • ADA real time embedded systems • Integrated project management • Accurate operations in numerical data processing • Rule based approach to information system development • Components reuse in knowledge-rich environments
Advanced Information Processing	19 projects including • Knowledge-based architecture for process control • Integration of symbolic and numeric learning techniques • Depth and motion analysis, Voice natural language • Knowledge based user friendly system • Low-cost high-performance multi-processor machines • Further development of PROLOG
Office Systems	23 projects including • Acquisition, compression & reproduction colour documents • Linguistic analyis of the European languages • Public data, voice and picture storage & retrieval systems • Knowledge aided recognition of continuous speech • Parallel architecture for networking linking OSI systems • Office systems research workstation for Europe
Computer Integrated Manufacture	10 projects including • European computer integrated manufacturing architecture • Concurrent algorithms and software for CAD and CAE • Predesign of flexible manufacturing systems • Communication network for manufacturing applications • Tools for economic evaluation of CIM in smaller companies • Knowledge based supervision in CIM

Figure 19 European—ESPRIT program

The fifth generation era takes us up to 1988 and all of these national programs are now entering their second phases, facing up to sixth generation priorities and objectives. It is interesting that Japan has again produced the most visionary proposals for the next generation of information technology. Figure 20 puts the fifth generation program in the context of the history of Japanese government funded research in information technology. The Postal Services proposal for an intelligent telephone system combining speech recognition with simultaneous translation targeted on 2002 is one example of the strategic planning involved.

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 20 Overview of Japanese information technology programs

However, the most remarkable Japanese proposal has been for a *Human Frontier* research program as shown in Figure 21 of which its sixth generation computing program is part. This involves international collaboration in research on the problems of the human species targeted on the improvement of the quality of life worldwide.

This proposal has a curious history because it was released by Japanese embassies in advance of the 1986 Summit meeting in Tokyo, yet Nakasone dropped it from his agenda. However, parts of it have been funded, notably $200M in biotechnology and brain science at the Riken laboratories.

The information technology component of the Human Frontier program is in the report, *Promotion of R&D on Electronics and Information Systems that may Complement or Substitute for Human Intelligence*, from the Subcommittee on Artificial Intelligence of The Council on Aerospace and Electronics Technology in Tokyo. The Council reported to the Ministry of Science and Technology in March 1985, using the term *knowledge science* for its subject matter and proposing the program shown in Figure 22. Whereas the fifth generation program is targeted on machine architectures using very-large-scale integrated circuits for artificial intelligence machines, the *sixth generation* program emphasizes the knowledge that has to be programmed into these machines. It calls for research into innovations in frontier high technology that will lead to societal, economic and cultural advancements. It is aimed at the expansion of human potential and the foundation of creative science.

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 21 Japanese proposed *Human Frontier* international research program

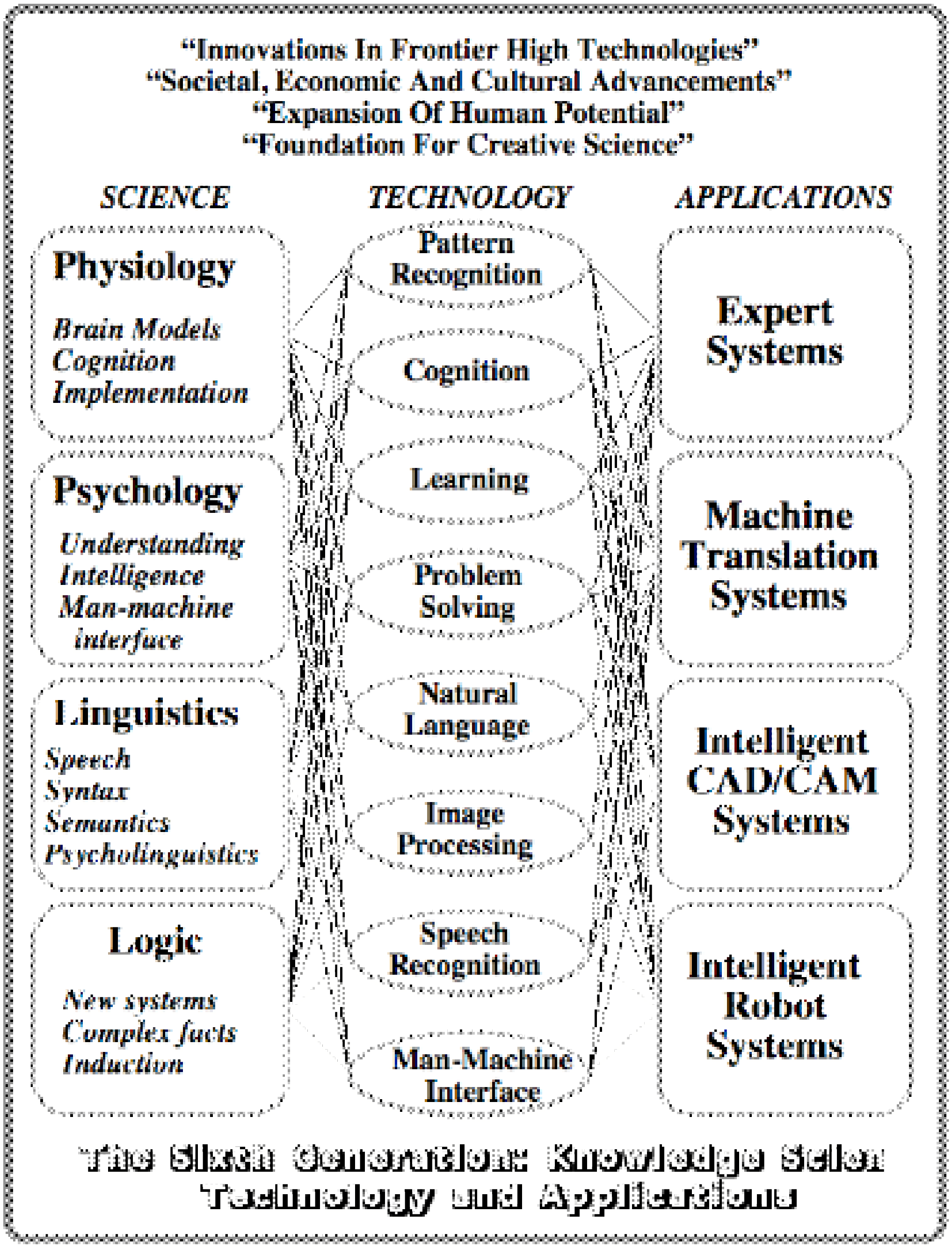

Figure 22 Japanese "sixth generation" program

The program sets a goal of developing complete theories of human intelligence that can be operationalized through computer programs. It proposes to put together multidisciplinary teams of computing scientists together with *neurologists*, *psychologists*, *linguists* and *philosophers*, in order to generate the technologies in the center column for applications in expert systems, machine translation, intelligent computer-aided design & manufacturing and intelligent robotics. One perspective on the sixth generation objectives is that they are consistent with the old adage that we cannot program what we do not understand. To create artificial intelligence requires a much greater comprehension of natural intelligence.

8 Summary and Conclusions

Figure 23 shows the state of the art of information technology in terms of computing and its interaction with the physical, social and knowledge worlds:

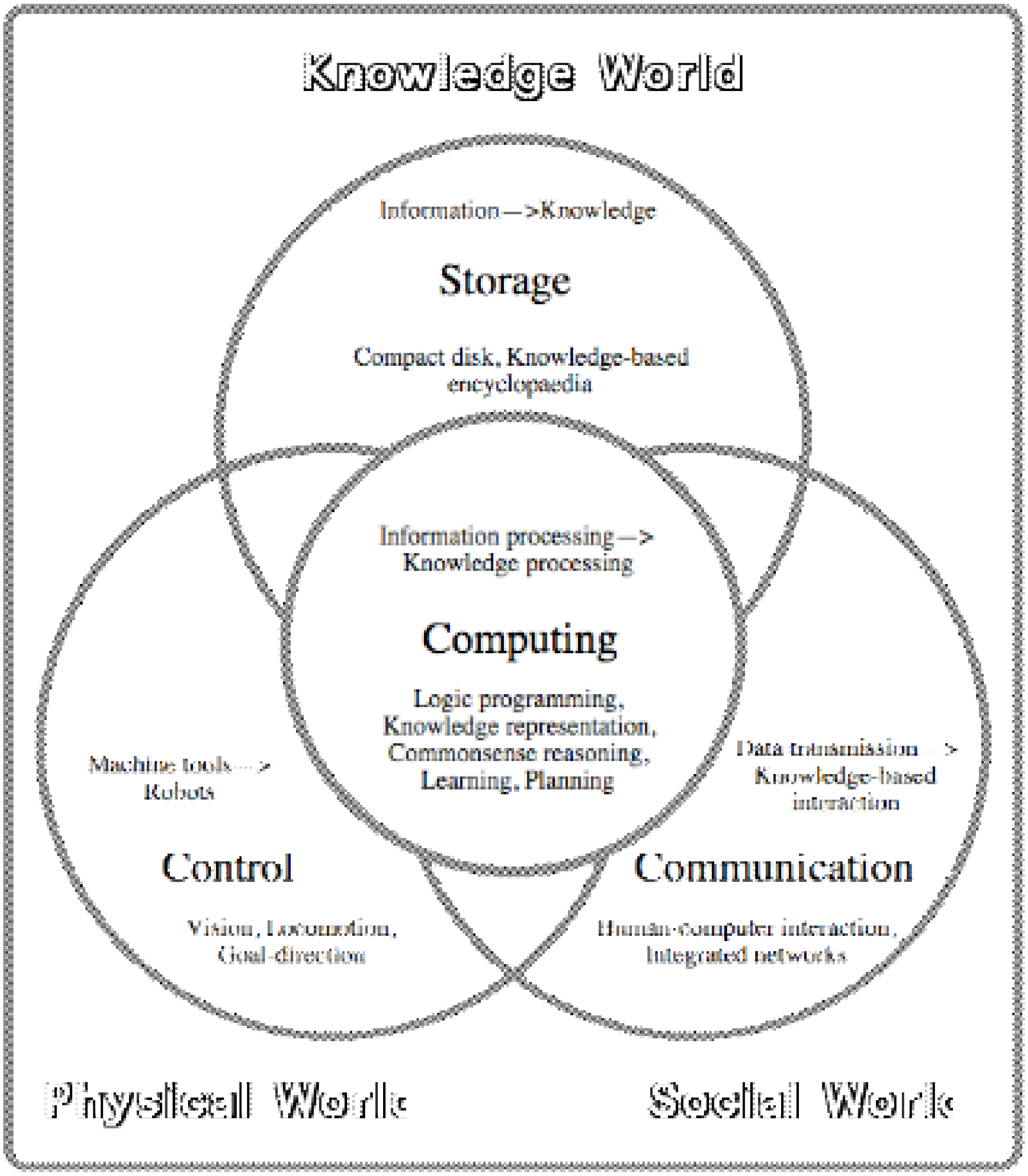

Figure 23 The state of the art in information technology

- At the center, the focus in computing is changing from information processing to knowledge processing and emphasizing the new technologies of logic programming, knowledge representation, commonsense reasoning, learning and planning.
- At the top, the focus in storage is changing from information to knowledge, with very high density compact disk storage allowing complete encyclopedias to be made available in low-cost personal computers. However, giving access to the knowledge in the encyclopedia as a

basis for automated dynamic reasoning, rather than a source of static data, is still awaiting breakthrough.

- At the lower left, the focus in control is changing from machine tools to robotics with research targeted on machine vision, locomotion and goal-direction. However, human vision and locomotion, are in many ways more difficult to emulate than the ‘higher’ cognitive functions of intelligence, and major breakthroughs are required to realize the full potential of robotics.
- At the lower right, the focus in communication is changing from data transmission to knowledge-based interaction with emphasis on human-computer interaction through integrated networks. The networking technology for total integration of the operational, developmental, administrative, legal and accounting functions of major organizations is already available. The managerial knowledge to restructure the organization to use this effectively is still many years away.

Much of what needs to be done in research, product development and application in terms of the advanced information technology of Figure 23 falls within the traditional disciplines of engineering. However, as the previous discussion of sixth generation developments suggests, there is also much of an immensely practical nature that requires major developments in disciplines not conventionally included in engineering. Figure 24 shows the many disciplines underlying knowledge engineering, the process of transferring skills from human experts to expert systems. Computing is now only one part of a support structure that includes not only psychology, linguistics, and their modern operational counterparts, cognitive science and computational linguistics, but also sociology and anthropology because of the essential socio-cultural components of human knowledge acquisition and transfer, and philosophy and system theory because of the foundational problems in the nature of knowledge. We are moving into a world of knowledge science whose structure encompasses all our traditional disciplines and professions, and some yet to come.

The development of knowledge science and knowledge technology in their own right is crucial to the generation of our future industries. Knowledge engineering and the knowledge economy are an essential component of our existence. The engineer and the entrepreneur must cooperate to create the foundations of future society. Life is risk. The universe of risk, the nature of the risks themselves, the significance of those risks to our civilization—all are changing as we enter the information age. Humanity is an entrepreneurial venture in survival and we are part of it.

Figure 24 The many disciplines underlying knowledge-based systems

Figure 25 is a light-hearted summary of the themes of this presentation, extrapolating the evolution of information technology way beyond any reasonable forecasting methodology. Its main weakness is that it does not take into account advances in genetic engineering and the space program that will make humanity in 2012 rather different from that of today.

The evolution of computing technology through data processing, information technology, and decision support, to knowledge-based systems has taken place. Research in machine learning and goal direction is sufficiently advanced for clear predictions of the next two stages of evolution to learning and purposeful systems. Beyond the end of the century we can only extrapolate that the hybrid bio-technical systems that we create in the convergence of genetic engineering and information technology will become a powerful social force in their own right. What "wisdom" will become in the next millennium is beyond our horizons, but the question is key to our understanding of future information technology and future society.

	Evolution	Definition	Buzzwords	Our view of computers	Computers' view of us
1956	**Data**	Uninterpreted numbers	Data processing	Fast, accurate & reliable	Slow, inaccurate & unreliable
1964	**Information**	Structured data	Information technology	Keep track of complex structures	Easily swamped by complexity
1972	**Decision**	Selecting information	Decision support	Always correct but rigid	Sometimes wrong but flexible
1980	**Knowledge**	Reasoning underlying decision	Knowledge science	First baby thoughts	How do they know so much?
1988	**Learning**	Acquiring knowledge	Inductive inference	Slow, inaccurate & unreliable	Slow and social but necessarily so
1996	**Purpose**	Directing learning	Autonomous systems	No sense of direction	How do they know what they want?
2004	**Power**	Achieving purpose	?	Not in my lifetime	Their ultimate goal
2012	**Wisdom**	Applying power reasonably	?	They don't have it	They don't have it

Figure 25 Evolution from data processing to knowledge processing and beyond

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