THE BIOSOMA

Reflections on the Synthesis of Biology, Society and Machines

George Bugliarello

Polytechnic
UNIVERSITY

THE BIOSOMA

REFLECTIONS ON THE SYNTHESIS OF BIOLOGY, SOCIETY AND MACHINES

George Bugliarello

Polytechnic University
Six MetroTech Center
Brooklyn, NY 11201

Printed in the United States of America.

Library of Congress Cataloging-in-Publication Data

Bugliarello, George
The Biosoma:
Reflections on the Synthesis of Biology, Society and Machines
George Bugliarello

Includes bibliographical references.

ISBN 0-918902-50-9

1. Machines
2. Biology
3. Society

I. Title
II. Bugliarello, George

THE BIOSOMA
Reflections on the Synthesis of Biology, Society and Machines

Figures

INTRODUCTION

Our lives as human beings have become inextricably intertwined with societal processes and organizations and with machines. I call this kind of intertwining of biology, society and machines *the biosoma*. This extended acronym for the complex entity formed by the combination and interaction of biological organisms, society and machines is introduced here just to avoid repeating "biological organisms, society and machines." It has no relation to the word *soma*, Greek for "body," or also "sacred mushroom," or, as used by Huxley in *Brave New World*, to denote a drug.

The intertwining of biology,[1] society and machines is nowhere more evident than in cities, in which today half of the world population lives. The cities are utterly dependent on water, energy and food supply systems, on telephones, computers, transportation systems and social organizations, from hospitals to schools to police to city government. It takes a disaster like the tragic destruction of the World Trade Center twin towers in New York City on September 11, 2001, to make us recognize the consequences of a failure of the biosoma, of the buildings and other machines, and of the societal entities to which we entrust our lives and on which we depend to extend our biological reach.

Technology, as the process human societies devise to produce and use machines and modify nature, is the quintessential and all pervasive biosoma phenomenon. It encompasses primary nature-modifying activities, such as engineering, medicine and agriculture, as well as supporting ones, from law to finance and management. But for its simplest manifestation, technology requires the synergy of individuals, machines and social organizations and depends profoundly both on an understanding of nature—on science—and on the capability to design. The outgrowths of technology include the ability to modify our biology through genetic engineering, to escape Earth's gravity through aerospace technology and even to wipe out much of life on Earth through weapons of mass destruction. Virtually every human activity—agriculture, commerce, education, health care, warfare, industry and more—depends directly or indirectly on our interactions as individuals with society and machines.

Despite the pervasiveness of such bio-socio-machine interactions, we rarely consider their broad implications. Yet, our future depends on understanding the different characteristics, potentials and pathologies of the three elements of a biosoma and the opportunities that a well-guided synergy can offer.

In many cases, the three biosoma components do not stay in balance because of differences in response times. The social element of a biosoma often responds slowly to innovations in machines, which frequently require new organizational patterns, new laws, the development of new perceptions and the evolution of new customs. An example of the difficulties in bringing about technological innovation is the countries of the former Soviet Union, where the remains of the rigid Soviet social structure and the associated frame of mind are still major obstacles.

Biological organisms, social systems and machines vary in performance because of their different natures. For one thing, a utilitarian machine—say a toaster—has a specifiable task, but the task or performance of biological organisms and of social entities may not be so easily defined. In addition, the different biosoma components are prone to generating different errors. Their varying characteristics can have serious implications for a biosoma's performance. The human component is bound to commit random errors in performance, and it is powerfully affected by psychological factors. For example, an air-traffic controller will make unpredictable errors, and they may be more frequent under stressful conditions. Society, too, is subject to random errors, which are highly volatile and idiosyncratic. As history demonstrates, society can generate grievous systematic errors such as those stemming from political or economic theories that are flawed or implemented too rapidly without the benefit of effective checks and balances.

Machines, unlike people and societies, are not likely to commit random errors in their performance if they are well designed and built. So we rely increasingly on them to strengthen the checks and balances of biological and social systems. This can be done with devices such as drugs or pacemakers that help to restore physiological balances, or with models or simulations that enhance society's ability to achieve a balanced solution to complex problems. One such problem is the control of damaging emissions to the atmosphere. Unfortunately, such checks and balances can also be achieved through the immense power of new weapons, as in a stalemate between nuclear powers.

On the other hand, machines can increase risks. They can fail because of systematic errors in design that may be hard to detect, as in the case of very complex software. As our dependence on machines increases, those that are designed to help restore the innate system of checks and balances of our biology may also, paradoxically, weaken them. For example, people with physical limitations (such as debilitating nearsightedness) might be kept alive by machines (eyeglasses). But if machines fail us or if, for whatever reason, we were to lose the ability to create eyeglasses and correct vision, these people would be at great risk and the recuperative capacity of the species would be weakened. These effects need to be clearly understood if the biosoma is to enhance rather than endanger us.

A fundamental challenge for our civilization is to identify and provide every individual with the minimal biosoma level that is essential for survival, health and human dignity. Civilization has little meaning if this minimum level is not met. It is a level that must extend beyond purely biological needs to encompass a set of indispensable machines and social interactions. To see how far we are from achieving it, one needs only to look at the Earth's more-than-one-billion poor or at the ways we destroy, often carelessly and inadvertently, human dignity.

Beyond this essential biosoma level, we can aspire to a level where the biological, social and machine components are well balanced, are sustainable indefinitely without destroying the environment, and enhance the human condition. These desirable levels can be achieved only if we succeed in avoiding imbalances among the three biosoma components. In a world where hunger remains rampant, machines and organizations hold the key to producing more food and distributing it efficiently and equitably. But machines can unduly influence the development of society and consume too many of our resources, or destroy us when used for war and terrorism. Similarly, in societies that are too powerful, may have few or no rights.

The synergy of humans, society and machines—the biosoma—is the fundamental cause of the unprecedented material prosperity of many nations. At the same time, however, the organized use of machines is increasingly dominating our daily life. It forces us to spend hours in congested traffic, it steadily makes our work more abstract and threatens its very ethos, leading to a deterioration of person-to-person interactions replaced with person-to-machine ones. Is our present condition transitory? Will it eventually lead to a more balanced and desirable biosoma, or will these trends be exacerbated? To approach these questions, we need to develop a much broader interdisciplinary education for everyone—specialists and non-specialists alike—so that all can understand the promise as well as the dangers that can arise from the interactions between biology, society and machines.

My purpose here is to reflect on the nature and implications of such interactions. The starting point—Part I—is a focus on the machine, the most recent of the three biosoma components and in many respects the least understood, in spite of its immense influence on our lives. This part may be heavy-going for the reader, even if I have tried to make it as easy as I could. It is, however, an essential premise to Part II, which deals with the biosoma.

I am an engineer, thus I bring to this quest for a synthesis a viewpoint different from that of a biologist or a social scientist.

Part I

THE MACHINE

CHAPTER 1. THE PERVASIVE MACHINE

The term machine comes from the ancient Greek *mechanè*, where it means, generally, artifact. But it can also have a pejorative connotation, as in machination, thus encompassing our ambivalence about certain aspects of technology.

Machines surround and affect us in virtually every manifestation of our lives—from houses to cars, from clothes to packaged foods, from how we communicate to how we do business and make war—or play. Machines give us protection from the elements and from our enemies; enable us to communicate with each other and to travel across the globe; help us to grow immense quantities of food; lighten our work and generate ever new kinds of jobs; entertain us; and help us fight disease. Without machines our world could not sustain the lives and aspirations of its six billion inhabitants. At the same time, however, because of the potential destructive power of machines, those very lives are at risk. And because of the ever greater pervasiveness of machines, our lives and our society are changing with dizzying speed, often with unforeseen consequences.

Yet, we give little thought to what a machine truly is and represents in our lives and our destiny, on how it differs fundamentally from the biological organisms that have created it, and which it complements and extends.

What Is A Machine?

A philosopher has said: "Nobody has yet provided a clear and cogent explanation of just what a 'machine' is in the current scheme of things.... The breathtaking modern development and the capacities and complexities of 'thinking machines' ... have also cost us any secure intellectual grasp on just what it is to be a machine." (Rescher, 1995). There is much confusion in defining what a machine is (Fig. 1), as many dictionary definitions show.[2] Beyond those definitions, Le Corbusier speaks of the city as a machine for living (Le Corbusier) and a contemporary engineer makes a distinction between machines and static artifacts (Billington). A humanist stated that "once we persuade ourselves that 'machine' need not connote iron or hard-ware...we can see mechanisms

Descartes (1600s)	Animals and humans are just elaborate machines
De La Mettrie (1700s)	"L'homme machine"
Picabia (1910s)	"Machine is part of human life – perhaps the very soul"
Le Corbusier (1920s)	"City as a machine for living"
Billington (1980s)	Structures *versus* machines
Kenner (1987)	"Once we persuade that 'machine' need not connote iron or hardware, that the word applies to any economical self-activating system for organizing resources, we can see mechanism anywhere [in the 19th century]"
Minsky (1980s & '90s)	The brain is a machine

Fig. 1. Confusion about What A Machine Is

everywhere in the [nineteenth] century resourcefulness at organizing and making accessible all that could be ascertained about the record of human speech" (Kenner). For Francis Picabia "the machine has become more than a mere adjunct of life. It is really a part of human life—perhaps its very soul" (Tomkins). The Webster dictionary definition of a machine as "an assemblage of parts...that transmit forces, motion and energy one to another in some predetermined manner and to some derived end" (Merriam-Webster) reinforces the perception already intrinsic in Aristotelian biology and reiterated by Descartes that humans could be viewed as advanced machines. This was also Julien de la Mettrie's view in his famous 1748 book *L'Homme Machine*. That view and perception is echoed in recent times by Minsky's sophisticated view of the brain as a machine (Minsky). There is, however, a larger point. Undoubtedly, much can be understood about biological organisms by using what we have learned from machines, and from the physical or engineering principles that we use in analyzing them (e.g., Bugliarello, 1977; Vogel). But we can benefit far more by taking a view of machines that, although broad, does not obliterate the differences between them and biological organisms—between the originator and its extension.

We can sort our way out of these difficulties by defining a machine as "an object that did not exist before in nature but is created by biological organisms by a metabiological process." With caution, we can extend the definition beyond objects, to some processes such as the design of software. We must be careful, however, to distinguish such processes from social ones, such as the parliamentary processes, which are also a creation—but one of a different nature—of biological organisms.

The term machine, thus defined, is very general. It encompasses all kinds of devices, far more than just mechanical ones. A computer program, a genetically engineered plant, a house, or, for that matter, a painting, are as much a machine as an automobile or an electric motor. None of them existed *a priori* in nature. None of them evolved from an original cell or organism or set of genes. As I shall stress later, machines cannot be represented in their totality by a branching out from a common origin. This is not to say that machines are not a product of nature. But they are a mediated product. They are meta-biological, profoundly different in the process of their creation from that of the organisms that invent and use them.

In the context of this general definition of machines, a painting and an automobile are both the creation of humans, but differ widely in how they are produced and, above all, in what they do and mean for each of us. We need to differentiate between what can be called definite or specific performance machines like the automobile—usually produced and specifiable by an engineering process—and machines that cannot be defined in terms of performance, such as a work of art. In these reflections I shall confine myself mainly to the former, which often, for the sake of brevity, I shall simply call machines (indefinite performance machines.)

A definite performance entity implies certainty. Certainty, in turn, often tends to imply inflexibility. Indefinite performance implies a certain amount of uncertainty and flexibility. Problems arise when the inflexibility of one entity is matched with the inflexibility of another, thus creating a totally inflexible system. This is why, matching machine to machine must be done carefully and why, often, man-machine systems are preferable to purely machine systems. Conversely, problems can also arise in matching two flexible entities, as the performance of the combination may become too unpredictable, calling for the discipline imposed by the machine. Bureaucracy, a typically inflexible social organization, is an endeavor to provide certainty in the performance of social tasks. If matched with further inflexibility, that of an individual bureaucrat or that of a definite performance machine, it can lead to nightmarish performance.

Even the distinction between definite and indefinite performance entities does not let us quite off the hook when it comes to defining what a machine is. Consider a poem. Clearly, it is not a machine, as it is a purely immaterial creation of the human mind. Similarly, education can be purely biological, to the extent that we can learn by ourselves without the help of others. (More commonly, however, it is bio-social, achieved through the interaction of pupil and teacher.) Thus, we need to distinguish between what is purely a biological process, such as the thoughts of the advanced organisms that we are, and a machine, a creation, tangible or intangible, of those thoughts, by which we change nature. Learning and poetry are natural processes of invention, even if more and more they use machines to great advantage, from the humble pen and sheet of paper to the dictionary and the word processor.

More complex is the issue of societal processes. They are metabiological, like the machine, and are encountered in different degrees not only in humans but also in many other living organisms. In humans, they rely increasingly on machines. However, they are so distinct from the biological organisms and processes that are their foundation, as to have acquired a life of their own, transcending that of the individual. Thousand-years-old institutions like the university or major organized religions are examples of that transcendence.

Still, our difficulties with definitions are not completely resolved. Consider, for example, a computer program. It can be viewed as a machine that activates another machine, the computer. But also it could be thought of as not being different from a poem—as a natural process in the mind of the programmer. To conclude this tortuous but necessary reasoning, we simply may have to accept that the definition of machine I have proposed, although quite general, still entails some ambiguities, and fits best, in a narrower sense, that of specifiable or definite performance artifacts.

Beauty, Art and the Machine

In this context, it is particularly illuminating to think of the question of beauty and of the relation of machines to art. Artwork is an indefinite performance entity, in the sense that its effect is very much in the eye of the beholder—it cannot be defined *a priori* with certainty by the artist or expressed in numbers. Thus, it cannot be judged by machine standards. Yet, the definite performance machine, with its specified performance characteristics and its power to expand our capabilities, has had an enormous impact on art. For instance, because of its ability to capture images, the machine has released art from the need to be representational. It has pushed art to abstraction, making it in the process even more of an indefinite performance entity, with performance in the eye of the beholder.

Today, some machines less simple than the scalpel or the paintbrush are also used to create art. Computer art is created through the mediation of a complex machine; its artistry is in the conception of the programs for the computer. The results once again are in the eye of the beholder. They are indefinite.

The fact that a machine, in the narrower sense, is a definite performance entity does not prevent it from having an artistic dimension, as quite evident in the great temples and cathedrals. However, beauty is not always the conscious goal of the creator of the definite performance machine, as evident by the absence in today's engineering curricula of any training in esthetics. Yet, some of the most impressive products of engineering have a beauty of their own, enhanced by the evidence of their functionality (e.g., Billington). The extreme of beauty through functionality of the Bauhaus movement of the 1920's and early '30s endeavored to create an architectural style as a result of a pure engineering process. The perception of beauty is an emotional experience. In Florman's felicitous expression, "the existential pleasures of engineering" are another subtle emotion in the creation of machines (Florman).

We recognize beauty when we see it, but what we recognize as beautiful can vary from culture to culture, as well as from individual to individual. Scientists find beauty in the phenomena they observe—in the simplicity of a physical law or in the structure of a molecule (Hoffmann). We see beauty in many animals, but not usually in all insects, and it is hard to say whether we find it in bacteria or viruses. Yet, we can find beauty in the DNA code and in the anatomy and physiology of cells. In definite performance machines, beauty is usually not a significant design goal, while obviously it may be one of the canons of the indefinite performance machines, of an artistic production. There are, however, also other emotions that artwork may seek to express and transmit. We can also find beauty in a social organization, if we think of it in the same way we think of a symphony or a ballet. The beauty is in how the organization comes together and performs.

Combinations of definite and indefinite performance entities, such as art and machines, should make it possible to blend the characteristics of both—the functional and the artistic. It should be possible, for instance, to create machines with individuality rather than mass-produced uniformity, and machines capable of conveying a sense of adventure. This could lead to new forms of art and architecture. Today, we are still too timid or ignorant to try many of these intriguing possibilities that would reduce the benumbing monotony of many of our daily environments. Yet, already some 40,000 years ago, Cro-Magnons had tools with an artistic dimension. Also, in ancient Athens, the social category of artisans included both artists and craftsmen (Meier).

Considering the nature of artwork can help in addressing the age-old question of the artistic value of the reproduction of a masterpiece. The masterpiece, as an artwork, is an indefinite performance artifact, but copying it is a machine-like process. The value of the copy lies in the exact, and therefore specifiable, reproduction of the features of the original. Hence, reproduction is a definite performance process. It can be judged objectively in terms of its success in reproducing the original. This does not mean that the process of copying may not require a high level of skills and artistry, or that a well-executed copy may not generate in us the same emotions as the original. But, intrinsically, copying is a very different process from creation. To think of an extreme analogy, in photography the artistry lies not in copying the subject being photographed, but in revealing some of its qualities through the image.

In brief, we may consider the definite performance realm (the realm of more narrowly defined "machines") as the realm of the functional and the indefinite performance realm as that of art. In the mental art of Picabia and in the ready-made art of Duchamp, formerly functional objects are used purely for their indefinite performance—for their meaning to the artist. This is a meaning that may not be shared by the viewer. Picabia's image of a sparkplug to represent a "Portrait of a Young American Girl In a State of Nudity" lost the meaning of its original functionality and became an artistic metaphor. Instead, in the so-called structural art, the definite performance functionality of the artifact, such as a bridge, is maintained, but the artifact is viewed—often *a posteriori*—in artistic terms (Fig. 2).

The difficulty in pursuing an aesthetic purpose in a functional device stems from the indefinite performance nature of art. There are no rigid aesthetic canons that can be codified and taught as part of the design process, say, of a bridge or a dam, as the functional is bound to dominate.

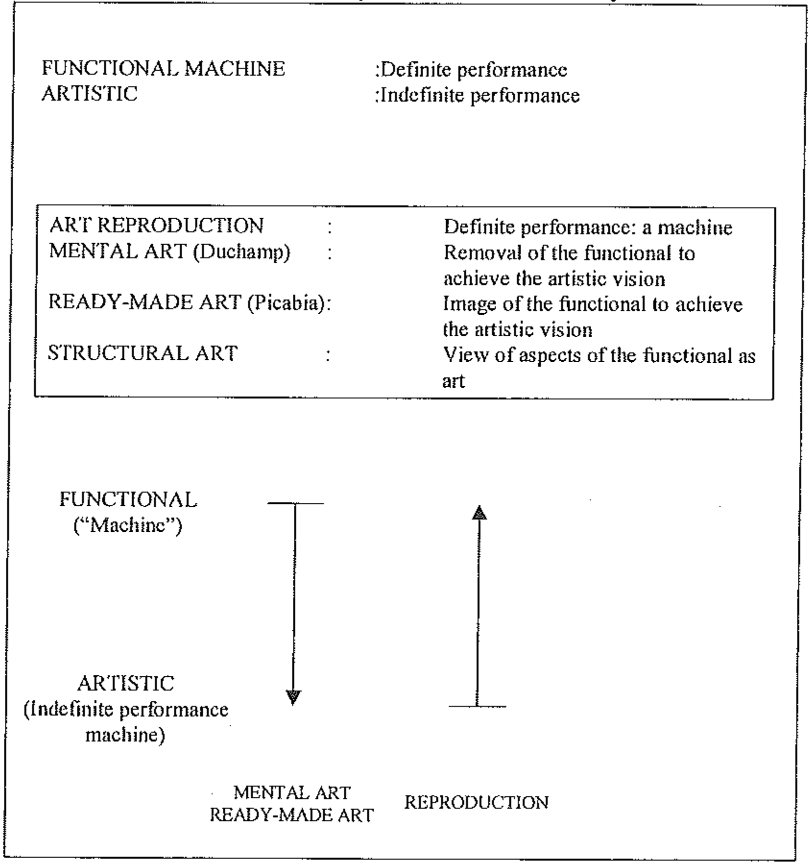

Fig. 2. Art and the Machine

CHAPTER 2. THE MACHINE IN THE EVOLUTIONARY CONTEXT

We often think of machines as a human invention, because the explosive growth of machines has occurred with humans, in the last six million years or so. But humans are by no means the only biological organisms that create and use machines. Some amoebae coat themselves with sand grains; several species of insects create machines, as exemplified by spider webs, anthills and beehives; birds and some fish build nests; beavers construct sturdy structures; chimps use sticks. (However, beehives and spider webs fit only ambiguously the definition of machines. They are produced directly by biological organisms with their own secreta, their own materials. A bird's nest, on the other hand, is unequivocally a machine, assembled from outside materials even if cemented by secreta). It has also been reported that in North Caledonia a crow seeks its food by fashioning and using standardized tools with the same kind of features of human shaped tools that are encountered after the lower Paleolithic period (Hunt).

The tools and other kinds of machines made or used by animals can all be viewed as specific or definite performance machines, given the fact that their purpose and performance are clearly definable. They can be called instinctive machines, as they are largely the product of instinct. It is only in the great burst of human machine creation and

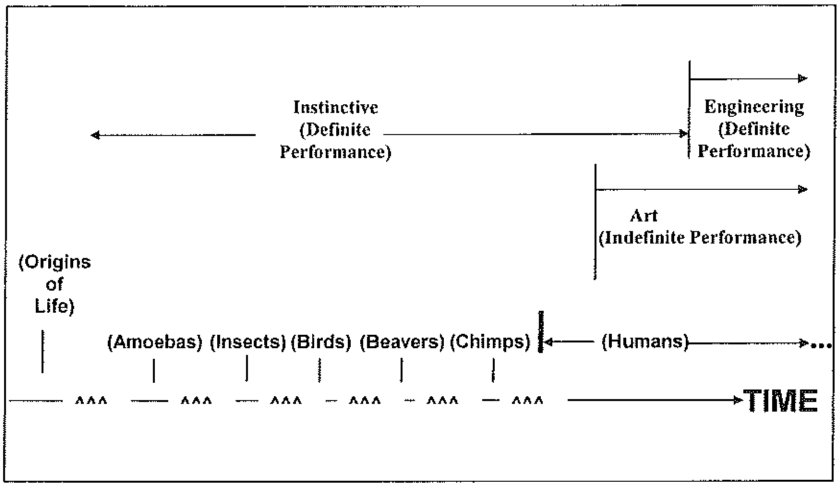

Fig. 3. Qualitative Time Sequence of Machine Development

Humans are not the only organisms to use or build machines, but they are the only ones to create art and engineered machines.

evolution that art—that is, indefinite performance machines—and engineered definite performance machines have occurred (Fig. 3).

The machine was from the beginning a key factor in differentiating us from primates. But, analogously to the explosion of diverse life forms that occurred late in the history of life (e.g., Kent), the proliferation of machines occurred late in human history (Fig. 4). In the Cambrian period some 500 million years ago, all sorts of life forms rapidly emerged and multiplied, as exemplified by the proliferation of species of algae, or by the emergence of over a thousand species of scorpions. With machines, something analogous to the Cambrian explosion occurred when modern humans came on stage about 40,000 years ago. It was undoubtedly helped by the evolution of language. Art emerged about 40,000 years ago, and so did specialization of production, and with it the onset of trade between human settlements even at a considerable distance from each other (Fig. 5).

By that time, we believe, what became modern humans, having started in Africa some 150,000 years ago, had spread to the Near East, India, China, Southeast Asia and Australia and were beginning to move toward Siberia, from where eventually they reached the American Continent (Burenhult). The great proliferation of machines occurred, however, only after the end of the last glacial period 12,000 years ago and, in an enormously accelerated fashion, only in the last 200 years. On a biological time scale

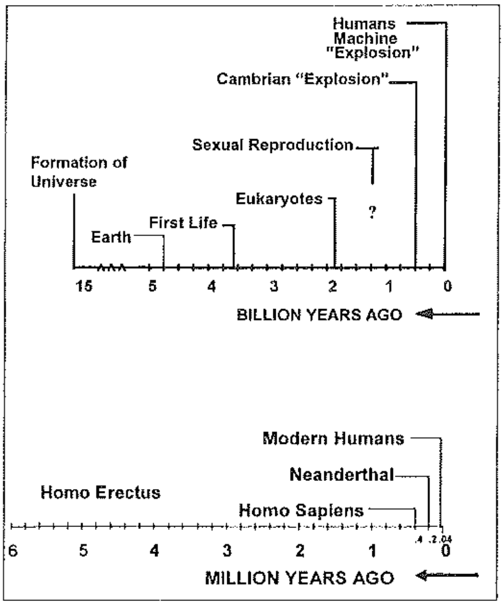

Fig. 4. The Universe, the Earth, Life and Humans—An Approximate Timetable

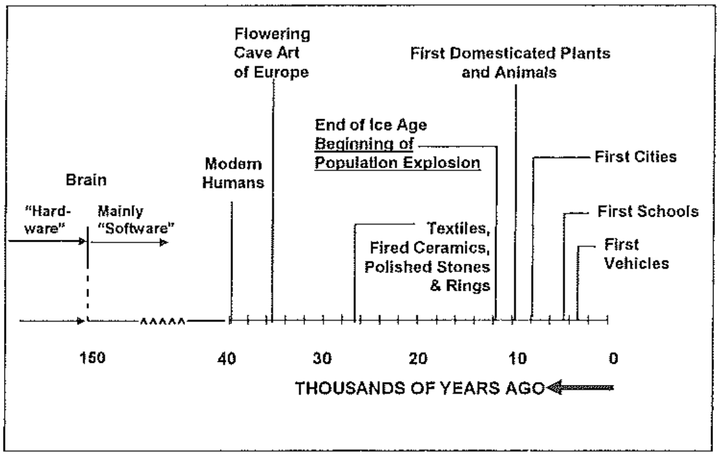

Fig. 5. Humans and the Machine "Explosion"

this development of human-made machines appears quite compressed, but a magnified time scale shows that it too required relatively long periods of evolution, exemplified by the evolution of transport machines. It took, for instance, several thousand years for vehicle springs to appear. Today, the speed of development of new designs is several orders of magnitude faster than that in macroscopic biological species and does not seem to abate (Fig. 6). In fact, it continues at a dizzyingly accelerating pace. One of the most dramatic examples is the achievement of aircraft speeds of six times the speed of sound within 50 years of the first Wright Brothers' flight of December 1903, and of spacecraft that circle the Earth ten times faster than the fastest aircraft. Even more dramatic are the advances in electronics. The jury is still out as to whether this fast pace of machine evolution will be sustained, because it is critically dependent on favorable societal conditions, as the stagnations in the middle ages in Europe and in other places and periods of history remind us.

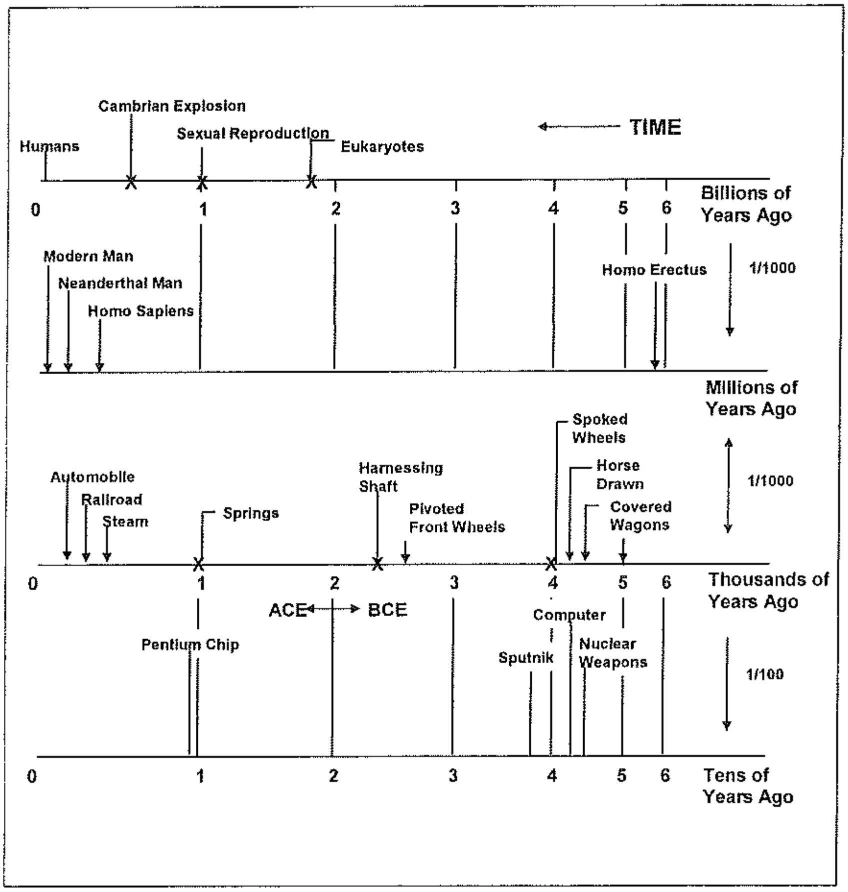

Fig. 6. The Different Time Scales of Biological, Human and Machine Evolution

The reasons for today's speed of machine creation are multiple: expanding synergies among different kinds of machines (as among computers, telecommunications and satellites), receptive social environments, ever newer niches created by machines in the market and in response to new needs, and the rapidity with which new designs can be produced, as particularly evident today in electronics and software. A key factor is the ever faster accumulation and diffusion of knowledge, facilitated by advances in communications, in information technology, and in knowledge institutions, from the university to the research laboratory, the patent system, and the "knowledge park" (Bugliarello, June 1996).

Machine Genesis

In the last half century, the feasibility of self-organization, self-assembly and self-replication of machines has become the subject of several studies. If we assume, as is increasingly justifiable and as discussed later, that the creation of advanced bio-machines and of machines by machines are attainable goals, the genesis of machines will have run its full course.

It could be summarized by this sequence (Fig. 7):

1) Biological organisms come into being in the environment.
2) Biological organisms evolve.
3) Biological organisms (particularly humans) and their society create machines.
4) Biological organisms, society and machines create ever more complex machines.
5) Biological organisms, society and machines modify biological organisms and create bio-machines.
6) Biological organisms, society and machines create self-reproducing machines.

Each step in this genesis is the result of a myriad of inventions in the biological, social, or machine domains. The creation of life from the inanimate environment, whether it occurred here on Earth or, possibly in space, implies the creation of a self-reproducing entity—a process that no one yet fully understands. The second step, the *evolution* of living organisms, is closely related to the first, and virtually inseparable from it. The fourth step denotes the ability of living organisms to create more complex machines with the help of simpler ones. We are just at the threshold of the last two steps, which are occurring in parallel. Their synergy is bound to open up new niches, including extraterrestrial ones, to the human reach, provided we retain control of the modification of biology and of the creation of bio-machines and self-reproducing machines.

1. ENVIRONMENT	⟹	BIO
2. BIO	⟹	BIO (EVOLUTION)
3. BIO + SOCIETY	⟹	MACHINES
4. BIO + SOCIETY + MACHINES	⟹	MORE COMPLEX MACHINES
5. BIO + SOCIETY + MACHINES	⟹	MODIFIED BIO AND BIO-MACHINES
6. BIO + SOCIETY + MACHINES	⟹	MACHINES ⟹ MACHINES ⟹... (machine self-reproduction)

Fig. 7. The Genesis of Machines

Why Machines?

Living organisms—whether birds, ants, chimps, or humans—use machines *to extend their biological capabilities*. We humans use machines to extend our senses (enabling us, for example, to utilize a broader portion of the electromagnetic spectrum than just visible light), our muscles (e.g., by motors or explosives), our brain (e.g., our memory capabilities by computers), or our skin (e.g., clothes, houses). By analogy with

Clausewitz' famous dictum about war, we could say that machines are the continuation of biology by other means. They are metabiological.

But the evolutionary meaning of machines goes beyond an extension of biological capabilities. Machines also *complement* our biology, and help us modify it. Unlike the case of the machine, the performance of a biological organism can be defined or specified only in part. If parameters such as blood pressure, weight, or eyesight, are quantifiable and definable, other aspects, such as feelings or thought, are not. They defy definition.[3] Thus we could call a biological organism a semi-definite performance entity.

	HUMAN	A TYPICAL MECHANICAL MACHINE	
WORK	20-30%		80-95%
SLEEP	20-30%		--------
ENTERTAINMENT	20%		--------
FEEDING	10%	MAINTENANCE	5-20%
OTHER	10-30%		

Fig. 8. The Different Time Budgets of Humans and Machines

The machine can complement biology because its performance characteristics differ from those of a biological organism. A machine does not need to sleep, or be entertained, and usually can work continuously, while a human typically works only twenty to thirty percent of the time (Fig. 8). More fundamentally, when complemented by a machine, a biological organism can achieve a more quantifiable or regular performance. The heart pacemaker regularizes the beats of the heart, and the clock disciplines the rhythm of our everyday life. Thus, we could say that the machine disciplines biology.

The machine can complement biology in still other ways. For instance, drugs—in essence, small machines for internal use—assist the organism when it cannot sustain the onslaught of rapidly multiplying infecting agents. The speed with which variants in drug design can be produced makes it possible to attempt to match the speed of mutations of an infecting agent. The race between drugs and drug-resistant micro-organisms is becoming ever more urgent and dramatic, with the reappearance of new forms of old diseases such as tuberculosis. Increasingly, the drugs themselves are *ad hoc* designed biological organisms, like antibiotics or DNA segments. The machine can also replace or enhance diseased or defective organs, or their function, as in the case of artificial hearts or kidneys, insulin injections and contact lenses.

Another aspect of how the machine complements biology is fashion. The machines that we call clothes not only protect us from the elements, but with their different shapes, colors and materials, help us accentuate our individuality and convey social messages. Or, as in the case of uniforms, they give us an appearance of uniformity that belies our individual biological differences.

Yet another facet of what machines do for us is to help us understand biological processes. We can study them in the light of what we have learned in creating machines, through the concepts of mechanics, thermodynamics, electrical engineering and computer science. This led to the 17th century vision of Descartes' and de la Mettrie's and to the contemporary view of Minsky of a biological organism as a machine. The computational power the machine enables us to analyze and model complex biological phenomena. Thus, advances in science and in machines tend to reduce ever more the domain of what is not quantifiable in biology.

Finally, the machine can help *modify biology*. This can be achieved through direct intervention (for instance, by modifying genes through advances in instrumentation and genetic engineering), but also through the social practices and environments the machine makes possible. An example are the changes in behavior, including nutrition and sleep schedules, associated with living in an increasingly urbanized environment.

Each of these metabiological capabilities is a two-edged sword. The machine may be too powerful and destructive, as in the military use of nuclear energy or in the hearing impairment from high acoustic magnifications. It may regiment us too much. It may leave behind those who do not have access to machines that have become indispensable, like the telephone or the computer. It may end up by reinforcing drug resistant strains; it may modify biology too dangerously; or, as is often the case, it may develop faster than our capacity to adapt. However, the machine also has a powerful spiritual influence on us. A cathedral, a temple, a mosque enhance our religiosity. An airplane, a ship or the Internet expand our horizons and give us new experiences.

CHAPTER 3. AN EVOLUTIONARY TURNING POINT

With the machine, there appears, in the history of the world, an immensely powerful entity that is transforming its very creators—biological organisms and society. At the end of the last glacial period, 12,000 years ago, the human population was small. Some believe that there might have been at that time perhaps no more than 10,000 humans—modern humans—versus about 100,000 some 400,000 years earlier (Takahata et al.). The key factor in the vertiginous growth of human population to today's six billion was a broad set of machine inventions, from textiles, pottery and metals to agriculture, cities and sanitation, coupled with a more benign environment.

This parallel and mutually reinforcing growth of machines and human society in the biosoma has brought us to an irreversible turning point in the evolution of our species (Fig. 9). Consciously or unconsciously, we are deviate from the normal bio-evolutionary process shaped by the interaction of a species and its environment. We are now entrusting our future to our ability to preserve indefinitely our species in the new environments we are creating through machines. It is a colossal evolutionary gamble that affects not only us, but virtually every other living species on Earth.

However, the gamble is also one that eventually all living organisms will have to take if they are to survive the end of the Earth. That event is so distant—several billion years from now—as to be beyond the realm of today's science and engineering, indeed beyond our concerns. Even the catastrophic threat of a large asteroid hitting the Earth, although much closer in time, is likely to be a million years or so away. But we could speculate whether our species' approach to survival through our machines is the only possible one. If we continue indefinitely to be the dominating influence on their evolution, might other species be denied the chance to create their own means of surviving on the Earth?

Although ultimately of paramount importance, the question of life surviving the end of the Earth is far less urgent than the implications of our turning our backs to the normal evolutionary process. We are doing so, roughly at the half-way point in the existence of the Earth, by increasingly modifying the environment with our machines—industry, houses, automobiles, power plants—and with the immense populations they make possible. Our environment today is in part natural and in part human-created or human-influenced. For instance, in a city, the ground on which we walk is mainly human-made (cemented pavements), the air we breath is also artificially modified when we heat or cool it, dehumidify or pollute it, the water we drink is fluoridated, or chlorinated, and many sounds around us (music, noise) are also human-generated. This is much less so, however, in the country, to which, impelled perhaps by an ancestral memory, we like to return for recreation.

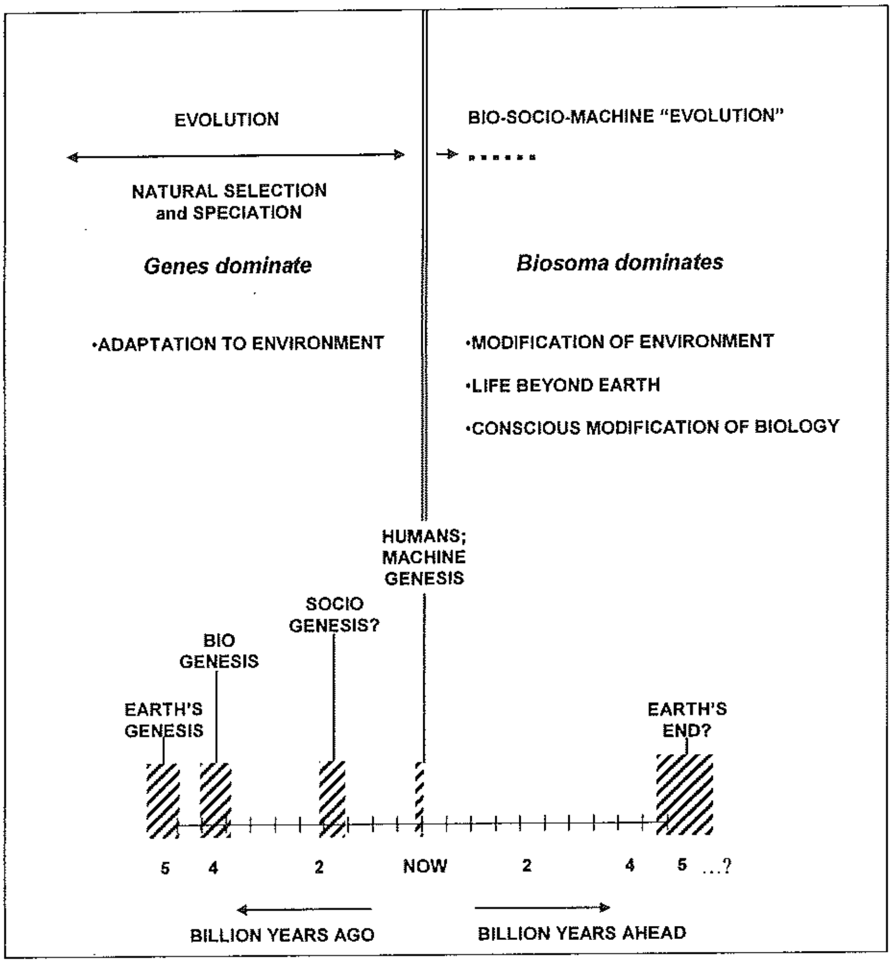

Fig. 9. The Biosoma and the Half-way Point in the Existence of the Earth

To the extent that the environment is affected or changed by our actions, it has become in some respects an artifact—a machine. It is, however, a peculiar kind of machine, an indefinite or, at best, a semi-definite performance one. We cannot fathom its impacts and we do not know quite how to control it. Even if we were to transform the environment by design and with wisdom, rather than by today's often ignorant or short-sighted actions, the fact remains that we are entrusting our hopes of beating the odds of extinction, which is the fate of most species on Earth, to our ability to use machines to help us feed ourselves and keep us healthy. It is sobering to think that only a small fraction, perhaps no more than 17 percent of all species that have been created, are now in existence. Those survival odds have become more chancy for us and other species not only because of the stresses on the environment, but also because of the enormous destructive power of our war machines. At the same time, however, if machines are used intelligently and wisely, we could envision an indefinitely extended future for our species. We could speculate, for instance, that even if human genes were to become "tired," we might be able to modify them.

Understanding the Nature of the Machine

To be successful in beating the odds against us, a better understanding of the nature of machines and of their interaction with biological organisms and society is imperative. The task is urgent. To quote Digby McLaren of the Royal Society of Canada: "We live at a crisis point in history and we are largely unaware" (McLaren).

Part of the difficulties we face in understanding machines and their implications is that our knowledge is traditionally compartmentalized, with high barriers separating most fields. Suffice it to look to our university curricula. Study of the social implications of the machine is often developed without much interaction between sociologists and engineers. As a result, the social complexities of the engineering design process tend to be overlooked. Until recently, economics dealt only to a limited extent with environmental issues. The law has tended to address only some machine issues (patents, construction law, maritime law or international law concerning satellites and frequency allocation) and only recently began to focus in depth on artificial organs and genetic engineering. Religions, traditionally, have not paid attention to machines, but for few exceptions, such as contraceptive devices. In engineering curricula—the domain of machine design—biology is usually ignored, except for bio- and environmental engineering and for a few schools where biology is now a required course for all engineering undergraduates. In turn, the biological sciences do not pay attention to metabiology. However, new academic programs that endeavor to relate science, technology and society are developing, and so are some initial notions of a new discipline, socio-technology (Bugliarello, 1973; Roy). Even the new inter-disciplines are limited in scope, however. Sociobiology, for example, originally intended as a broad synthesis, has focused primarily on genes as a cause of biological behavior (Wilson, 1975), and bioengineering tends to focus more on the applications of machines and machine concepts to biology than *vice versa*.

CHAPTER 4. BIOLOGICAL ORGANISMS AND MACHINES

A comparison of the machine with the entity responsible for its genesis—the biological organism—brings out parallelisms and differences that are key to understanding the machine in its role, impact and potentials. Here I will underscore only the most evident ones.

Design

Biological organisms create their own purpose, self-assemble and self-replicate (Fig. 10). A machine's purpose, instead, comes from the outside and self-replication and self-assembly are not intrinsic capabilities. The purpose is imparted to a machine by its designer—exogenously—rather than being embedded in a "genetic" patrimony of the machine, or, for that matter, in the genes of the designer.[4] However, the memory of a design can be preserved and is itself a machine—an information machine, such as a drawing, a text, or a computer program. (We may note that in the absence of such memory, archeology—as an attempt to discover the function and method of design of artifacts of the past—is, in part, reverse engineering, as in our efforts to understand how the pyramids were built). Thus far, a machine cannot self-assemble or self-replicate, except for the vexing example of computer viruses. Conceptually, in the second half of the twentieth century, some starts were made in this direction, beginning, I believe, with Von Neumann (Von Neumann). A continued impulse comes from the hope of creating self-assembling factories in space (Freitas and Zachary) and from the studies—more modest in scope but of fundamental importance—of self-assembling layers of molecules.

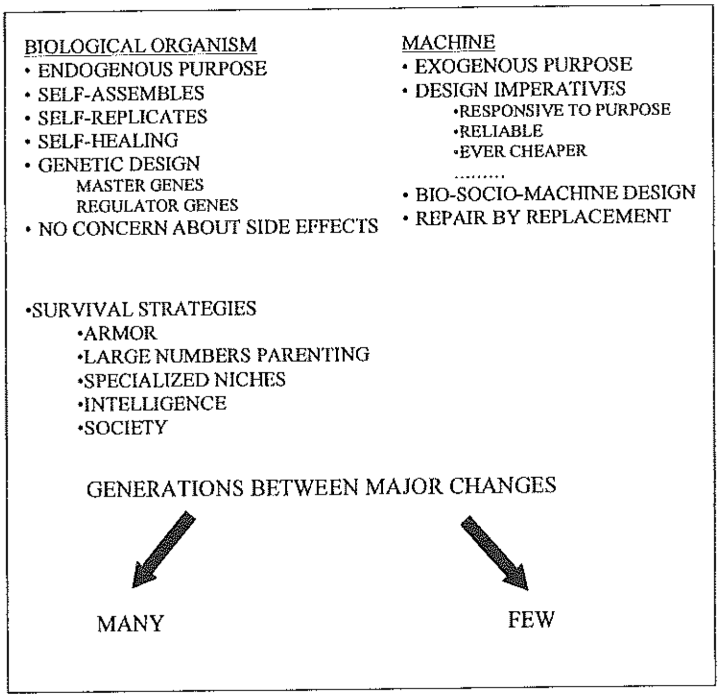

Fig. 10. The Design Process —
Biological Organism *versus* Machine

There are obviously profound differences in the specifics of the design process of biological organisms and machines. The "design" agents of some biological organisms—themselves the result of a complex and far from well understood evolutionary process—seem to be two sets of genes. Master/selector genes can make infrequent but major changes, typically after thousands of generations, while regulatory genes are responsible for more frequent but minor changes. It may also be that the so-called "junk" DNA, the portion of the DNA molecule for which we have not yet ascertained a function, is the incubator of major new mutations—major changes in design that eventually emerge. Generally, however, sudden and very large mutations are not successful.

For machines, new designs, analogous in a sense to a new set of master genes, stem from the combination of previous design knowledge of the designer with new design knowledge achieved through research, inventions and experience. Once a new machine design is created, it often can be extended for quite some time through a series of conceptually small variations, somewhat analogous to those caused by regulatory genes, until an entirely new design becomes necessary or desirable. For instance, an initial and satisfactory bridge design may become so lightened in successive designs that it can lead to disaster. This was the case for the collapse of the Tacoma Narrows Bridge in 1940, a bridge that was a conceptual descendent of the Brooklyn Bridge of the late 1870's (Petroski).

What constitutes a new generation has diff-

CELLULAR BIOLOGICAL ORGANISM	MACHINE
• INTEGRATION OF SYSTEMS	
BASIC MODULE: CELL	BASIC MODULE? CONSTRUCTION: •BY MOLECULES & ATOMS •BY LARGER AGGREGATES
BRAIN: •"HARD WIRING" •POST-NATAL DESIGN FIXING (Plasticity)	
DESIGN CONSTRAINTS (FLUIDS, ENERGY, COMMUNICATIONS)	GREATER DESIGN FREEDOM e.g. "EYE IN HAND" SPACE ENVIRONMENTS
UNSTABLE EQUILIBRIUM	THERMODYNAMICALLY STABLE
INTRINSICALLY RECYCLABLE	

DURABLE INVENTIONS

BIOLOGICAL ORGANISMS	MACHINES
PROTEINS	LEVERS
QUATERNARY CODES	SPRINGS
RNA, DNA	WEDGES
HORMONES	GEARS
GENES	RELAYS
EYES	ELECTRIC MOTORS
TEETH	WHEELS
BLOOD	BINARY CODES
PERISTALSIS	MATERIALS
....	METALS
	CERAMICS
	PLASTICS
	....

Fig. 11. Design Characteristics
Biological Organisms *versus* Machines

erent meaning in the domains of biology and of machines. In biological organisms, a new generation occurs every time the previous one gives birth. With machines, where there is no self-replication and the same machine could in principle be identically reproduced *ad infinitum*, we talk of a new generation only when there is a change in design or in the production process. For a long time the Ford Model T and the Volkswagen, the two longest lasting automobile designs, were reproduced with virtually no change ("Fordism"). Later, minor changes were introduced to improve the original designs. New car generations began to succeed each other at a very rapid pace only with "Sloanism," the philosophy of changing car models every year introduced in the 1930s by General Motors.

Further, it is useful to compare *design characteristics* of biological organisms and machines (Fig. 11). All cellular biological organisms are liquid-based systems, and thus able to function only in a relatively narrow environmental range. The machine, not being confined to a liquid base, can function in a much broader environmental range: in a vacuum, deep into space, at the bottom of the deepest oceans, or in the craters of volcanoes, making it possible for us to explore environments otherwise denied to us by our biology.

A cellular biological organism is a system of systems. It is a modular structure in which the basic module, the cell, combines with other cells to form larger moduli, as suborgans and organs. The cell itself is a very complex system in unstable thermodynamic equilibrium, constantly fighting denaturation and, for most cells, constantly renovating and changing itself. A machine also is a system, at times a very complex one. It is usually thermodynamically stable and it is not always designed modularly (for instance, except for the nano-atomic structure of metal, a steel beam has no modules, but a TV does). In the case of software, however, modular designs are taking hold very rapidly, to reduce the high costs of designing *ex novo* for every new application. In the case of hardware, only recently have we begun to design and articulate modules at the molecular or atomic scale, e.g., to design a microchip or a nanomachine molecule by molecule. Thus, while in biological organisms the trend of complexity and sophistication has been from the single cell to large assemblies of specialized cells, in machines ever greater sophistication is being sought today by progressing toward smaller and smaller dimensions of assemblies. However, once the engineering at the atomic level is mastered, the trend will reverse and larger machines will be built starting from that level.

Similarly, and revealing of the engineering nature of genetic engineering, it will be possible to build new, complex biological organisms by starting from a reengineered cellular level. Napoleon said that every soldier had in his knapsack a marshal's baton—the potential to attain the highest ranks. We could say the same of a cell, as it contains the genetic information of the entire organism and hence could grow, in principle, into it.[5] But we cannot say this of an inanimate machine element—at the nano level or any other level—at least until the ability to self-assemble is achieved. Until then, the germ of the growth of a machine and the marshal's baton will continue to reside in the mind of the designer.

Finally, when both the worlds of biology and machines find a useful invention, they latch onto it and tend to employ it in many different versions throughout their "designs." This is the case of proteins, quaternary codes, RNA, DNA and genes. Eyes, teeth, bones, blood, peristalsis and so on, are also used repeatedly in biological "designs."[6] Similarly, levers, springs, gears, hinges, relays, switches, actuators, binary codes and generic computer routines—just to mention a few from a very long and rapidly growing list—are used repeatedly in machines. The biological evolution that has produced biological inventions is not a continuous process but one that has occurred through bursts of "radiation" followed, for a number of species, by a long stasis. (This radiation comes generally from the crossing of two species, the hybrid being originally sterile, but then ceasing to be so by natural doubling of DNA.) Similarly, there are "radiated" bursts in the creation of machines, as those that emanated from the invention of steam machines and the Industrial Revolution, from the invention of the internal combustion engine, from electronics and the computer and from genetic engineering.

Biological inventions can hold great interest for the engineer as "proofs of concept"—as achievements that point the way, potentially, to feasibility in the machine domain. Take, for example, flat ribo-proteins, crystal-like structures which are precisely organized and folded. In earlier biological times, proteins were very much "mushy," and because of that, were not initially the powerful catalyzers they are now. Flat ribo-proteins are crystal-like, are orderly, and represent a durable invention. They are truly an engineer's dream and are strong candidates for survival, even in a heavy-radiation environment, because radiation does not damage them; it actually reinforces their crystal-like structure. Also, to the engineer, the RNA can be even more interesting than DNA because it performs not only functions of the DNA (which contains only information), but also many other tasks.

A biological invention as momentous as that of the gene, but less easily definable, is complexity, the process that at a certain moment led to the evolution of simple life forms into more complex ones. Complexity is manifest in a society of cells which communicate by means of physical or chemical signals, presumably at first unchanneled, then through interior liquid and nerve channels. Within a cell, too, information in the form of chemical, thermal or mechanical gradients enables the cell to compute and to communicate with other cells. Always within the cell, energy is used to maintain equilibrium and to carry out the cell's work. Its byproduct is waste expelled to the environment. The brain, as the most advanced manifestation of that complexity, far out-distances the complexity of other organs and has made possible human consciousness, judgment and morality. In contrast, machines are still far away from even approaching the complexity of biological organisms, let alone specifically that of the brain, and await some new design inventions.

There are, however, enormous differences between biological organisms and machine designs in terms of the speed with which new inventions can be adapted to different environments and needs. With machines, once the fundamental idea is developed—for example, the radio, the car, the airplane—change can occur very rapidly. Computers further speed up the process, by enabling designers to exchange information instantaneously, and to simulate a design on the screen, rather than as a physical prototype. Evolution and diffusion of fundamental biological "inventions," such as proteins, cells or teeth, is much slower, because even simple changes must occur within the DNA before they can burst out. Thus the machine has an enormous advantage in terms of speed of change of its designs.

The agent of creativity in biological organisms is the process of evolution. In machines, the creation of new kinds of machines occurs through invention. But *invention* alone does not suffice to successfully create new machines. *Innovation* is needed to transform an invention into useful products and processes. This is why today there is such a great concentration on technological innovation—on endeavoring to understand its characteristics, and the reason for its rapid pace, epitomized by micro-electronics. (The market for electronic solid state components has grown now for two decades at about thirty percent a year, making the gap between fundamental research and invention and application very short.) Thus, unlike biological organisms, the process of creation of machines in a rapidly evolving area of technology is forced to start before all the required information has been assembled—indeed, at times, before an invention is complete. This is risky for the inventor, and may be risky for society if it involves untested machines of potentially great societal or environmental impact.

Biological *versus* Machine Memories

Memory in the brain of a biological organism is in part congenital, embedded in the genes, and in part acquired through the experiences of the individual. The amount of information that forms the acquired memory starts with *tabula rasa* and increases with time, until, later in life, reduced blood supply and the death of brain cells start reducing it, together with the ability to retrieve it.

In machines, the equivalent of genetic memory is contained in some elements of hardware and in software, a system of instructions embedded in the machine from the outside. With appropriate design, memories can also be acquired through mechanisms that record the interactions of the machine with its environment, as in the case of a flight recorder, and that can also guide future operations of the machine, as in the case of adaptive designs. Unlike a biological organism constrained by the dimensions of the brain (in the case of mammalians, largely determined by those of the birth canal), potentially the amount of memory capacity that a machine can acquire or with which it can be endowed is immensely expandable.

Today, the investments in software for computers (as memory and instructions) have become quite high, in comparison to the hardware costs. Thus, when it comes to building the memory and logical capacity of machines, it is usually convenient to design a hardware substratum that can be replaced modularly, and to make the software as adaptable as possible to changes in capacity and in type of machine.

Several other characteristics of biological brains are potentially significant models for the design of machine memory and logical capacity. In the biological brain, imperfect connections among the brain cells (neurons) are eliminated, and frequently used connections reinforced, thus increasing the efficiency of handling information. In the biological brain, furthermore, cells die, and in certain cases are replaced by new cells. (This seems to occur, for instance, in squirrels. Every season, they need to remember anew where their stashes of food are located, but with their limited brain capacity, they cannot afford to be encumbered by the storage of old information from previous seasons.) In machines, given the inability, at least as of now, to regenerate its memory or logical elements, these elements do not "die" purposefully. In the case of self-adaptive machines—particularly very small self-adaptive ones—it could be interesting, however, to explore whether there are advantages to regenerating the hardware, *versus* reprogramming the software.[7]

Further on Design

The design which guides the construction and operation of a machine is the imaging of something that did not exist before. It is the product of human thought, which is a natural process, even if inevitably influenced by the machines that surround us. Unlike mathematical thought, however, which can be context-free, engineering thought—the thought that guides the design—is not completely abstract, as it aims at creating a new reality.

Knowledge of design is a social, or more properly, bio-social activity, the result of the thoughts of several designers and of their experience with several designs. These thoughts and experiences typically become codified in a design theory or in a more general body of design knowledge. The same goes, to a certain extent, for literature, where the individual thoughts of the writer are stimulated by the thoughts, written or spoken, of others—by the writer's social environment.

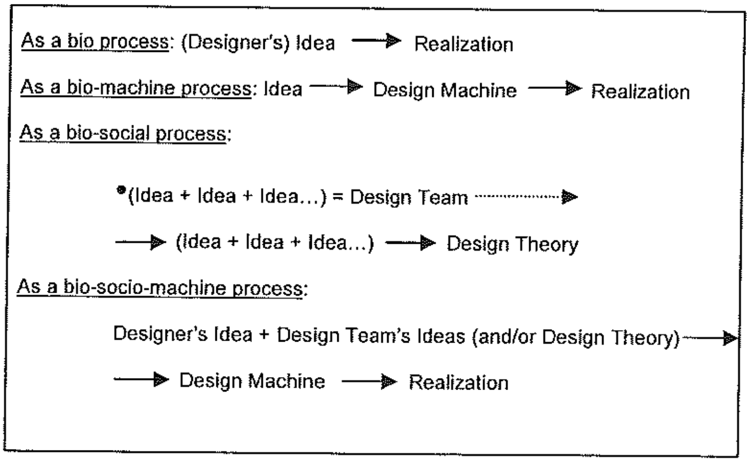

Fig. 12. The Progression of Complexity in the Design Process

The knowledge of design does not exist *a priori* in nature. But when the theory of design and the conception of a design leave the mind of the designer, they become embedded in drawings, papers, computer programs—that is, in machines—making design a bio-socio-machine process of increaseing complexity (Fig. 12). In effect, they become embedded in an artifact, tangible or intangible, which is a set of instructions for the creation or operation of another artifact. Those instructions, when they are realized, that is, when the conception in the mind of the designer is actuated, become the final artifact—the bridge, house, airplane, or computer (Fig. 13). There are, however, ambiguities. For instance, consider the difference between an oral transmission of thought (such as that which later became codified in the *Odyssey*) and the written transmission. Is the oral transmission a machine? No, even if it can be machine-like in its accuracy. Only when the thought is transferred to a machine does it acquire characteristics of a machine. Thus, the written form of a poem certainly did not exist in nature; it is, therefore, in a sense, a machine—albeit, as a work of art, an indefinite performance one. The separation is a subtle one.

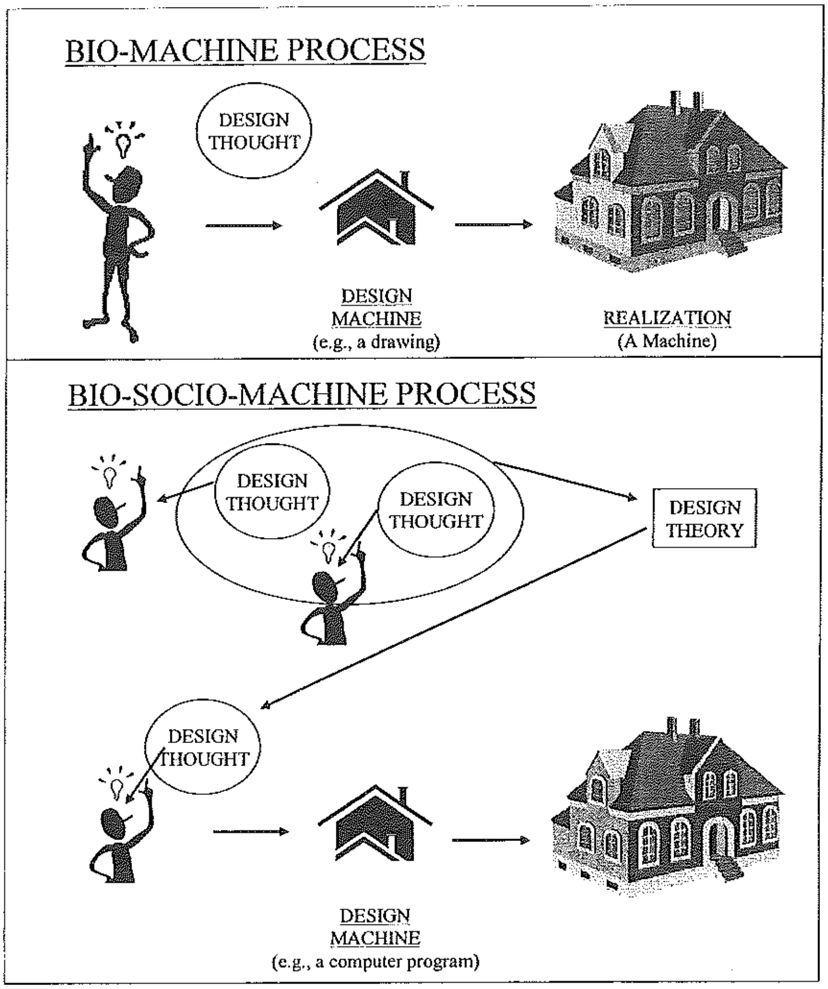

Fig. 13. Design - A Bio-Social-Machine Process

The imagining of something that did not exist before, to guide the construction or operation of a machine (a building, a computer, a piece of software, indeed also a sculpture, etc.)

To continue to elaborate, human thought is a biological process, or a bio-social one when it is influenced by the interaction with the thoughts of other humans. When committed, say, to paper, thought becomes embodied in a machine—a book, a drawing or a newspaper—which affects, by its diffusion, the way other humans think or operate.

Ethics

Like the thought of which it is a product, ethics has a human biological substratum which is augmented by education, that is, by a social process.[8] Social ethics is initially based on biology, but increasingly has expanded beyond the pure biological realm to address the complexities of society. The machine, intrinsically, does not have an ethic of its own, other than a projection onto it of the social and biological ethics of its designers. However, we can think of the possibility of creating advanced machines endowed with some sort of judgment, intended at least as the ability to develop heuristically a set of rules guiding their interaction with their surroundings. On a global scale, the confluence and integration of human, machine and societal consciousnesses, each with its peculiar characteristics, makes it possible to think of the attainment of a global consciousness, that is, of a higher form of intelligence—a hyperintelligence (Bugliarello, 1990). The consequence may be at long last the onset of that global morality that still eludes us.

Production

The biological world usually insures survival through self-replication of large numbers of specimens, a production process which cannot be stopped for retooling and hence favors small continuous mutations, as pointed out earlier. (In more advanced animals, however, survival relies more on parenting and social cooperation than on large numbers of offspring.) In machines, when large numbers are called for, they are achieved through mass production. This makes possible large and sudden changes in design, since an assembly line can be stopped and modified at will. However, while mass production of a rigorously replicated item has a number of advantages, it can be dangerous if the design has a serious flaw, now endlessly replicated. Mass production can also breed anomy because of its monotony. Hence the aspiration to achieve, within some limits, machine individuality, inspired by the individuality of the biological production process. Clearly, that individuality cannot be at the cost of relinquishing characteristics such as precision and reliability, that make machines valuable as complements to our biology.

Niches

Biological organisms must find in the ecosystem the niches in which they can survive. Machines must survive instead in the marketplace, or, more generally, by responding to a need. For biological organisms, the seeking of niches is driven from within. It is an autonomous activity. In machines, the niches are being sought by the designers and the producers. However, it is not impossible to imagine that, given some rules, some machines could find their own niches by seeking autonomously the best environments in which they can operate. Some robots or software agents do just that.

Biological organisms and machines not only utilize existing niches, but can also create new ones. In the biological domain, the emergence of trees and grasses created new niches for a multitude of species; the first sea animals that developed the ability to function also in air opened up a vast new domain to animal life on land. In the case of machines, any major technological development, like any major biological one, creates a new niche. The emergence of urban agglomerates created an opportunity for elevators, streetcars and lighting; the progression from smoke signals to optical ones to the telegraph, telephone, radio and television, created new market niches at every step.

The simple Model T had no electric starter, no safety glass, no fuel pump (the fuel was fed to the engine by gravity), no RPM meter, no cigarette lighter, no electric window lifters, no heater, no air conditioner, no safety belts, no air bags, no dome light, no windshield spray jets, no cruise control, no lubricant additives, no gas additives, no automatic shift, no *ad hoc* antifreeze, no self-sealing tires and no steel belted radials. Each one of these products came with the evolution of the automobile and represented new niches for new machines. Those niches became complemented by gas stations, traffic lights, parking lots, toll gates and car transporters, as well as by new societal organizations, or processes from auto dealerships to auto insurance to bureaus of motor vehicles. At times, we wish some new technological niches would not have emerged, such as the use of glue vapors as a drug.

As a particular kind of machine becomes obsolete, some niches disappear, but machines that operate in those niches may find use in new niches. A classic example is the preheating engines for Italian World War II military airplanes, that after the war were used as motors for the very successful Vespa scooter. Finding new niches for machines that have lost their original function is particularly pressing in the conversion from military to civilian technologies.

At times, different biological organisms compete in a given niche. This is also the case with machines, as exemplified in the 1990's by the competition in the same market between Apple computers and Microsoft-using computers, or, in the early 1930s, between Chevrolets and Model T Fords, which led to the demise of the latter. If successful in a niche, a machine may be produced in large numbers, but there is always a potential of severe environmental damage when the "evolutionary" test of a new machine is only a viable *market* niche, rather than also a viable *ecological* one. Thus, the jury is still out about the long-term global environmental impact of the automobile and of today's nuclear powerplants. There are, however, machines deliberately designed to improve the environment, for which a viable role in the ecology is the precondition of market success. Sewage treatment plants, for example, have proliferated because of their success in reducing water-borne pollution, albeit at a high financial cost unaffordable by much of the developing world. (A response to the needs of the developing world requires new kinds of treatment plants, such as those based on the use of pollution-absorbing biological organisms—plants, microorganisms, as well as some higher life forms.)

In general, in machines:

- the rate of niche creation is very rapid in terms of geological time, as exemplified by the sequence train, bicycle, automobile, airplane in a span of less than one hundred years
- new designs in a given niche are also developed very quickly, as in the evolution of microchips and the personal computer
- niches close to each other may merge or synergize, as is the case of telecommunications and information technology.

Because of these characteristics and the fact that the production of new machines can occur much faster than social awareness of their consequences, the biological, social and ecological impact of machines can be enormous. Social awareness, of course, is culture-specific. For example, consciousness of environmental impacts has been much more developed in the West than in the former Soviet Union, where one encounters some of the most horrific examples of environmental deterioration.

Failures

Biological organisms, including the designers of machines, learn through failures. Intrinsic failures of a physical, chemical or systemic nature are bound to occur in any biological organism or machine. Examples in machines range from material fatigue to corrosion, instabilities, faulty processing of instructions, and overall bad designs. In humans, whose "design" has been fixed for thousands of generations, one cannot speak of intrinsic design errors for the species (but one can think of further evolutions of our biological design). The intrinsic failures, rather, are failures of "production," caused by genetic errors in an individual or group of individuals that may result, for example, in biochemical imbalances or skeletal, neurological and cardiovascular diseases.

Other diseases, however, are due to extrinsic causes, such as a changed environment or an onslaught of infections. Similarly, in the realm of machines, an automobile designed for paved highways may break down if driven over boulder-strewn terrain. Some animals cease to reproduce in captivity and we humans suffer higher rates of heart disease in the stressful urban environments that are so different from the natural ones from which we emerged as a species. However, with both machines and biological organisms, the ability to survive these extrinsic failures may open up new niches in which they can successfully operate. Foxes, dogs and cats have adapted to urban environments, and the Ford Model T became an ideal vehicle for farmers because it could also function over muddy roads.

In general, machines and biological organisms have similar failure patterns: high number of failures at the beginning and at the end of their lives and moderate in between (Fig. 14). In a machine, the designer endeavors to reduce failures in the initial phase by better quality control and by simulating, typically by computer, the behavior of the machine to guard against surprises. For the end of the life cycle of the machine, the designer seeks to make the failures more predictable, to delay their occurrence through maintenance and, when they eventually happen, to avoid catastrophic consequences.

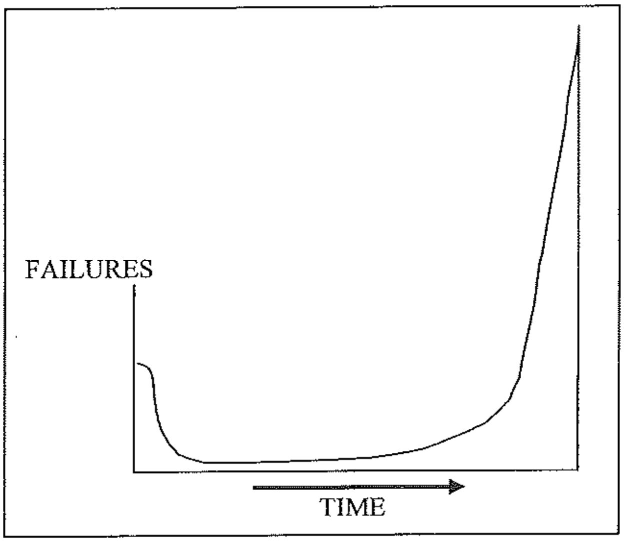

Fig. 14. Typical Failure Patterns of Living Organisms and Machines

In biological organisms, early life failures can be reduced by greater care. In humans this means not only better prenatal and perinatal care, but also better education of parents and children. The inevitable end of life failures can be postponed by health maintenance, not unlike the case of machines. This characteristic failure pattern also applies to decision-making, or intellectual activities in general, with a higher rate of failure initially, when we are younger, because of inexperience, and at the other extreme, when we are older, because of overconfidence or mental deterioration.

The typical failure curve in Fig. 14 is also encountered in the social domain. Social organizations have a high failure rate at the beginning and a decreasing probability of survival after a varying period of maturity. Usually, we have a fairly clear understanding of the causes of failures in machines, such as flaws in design or material failures. But still we do not quite understand what happens in semi-definite performance entities—in biological organisms and social organizations—when we talk of human or social errors. Machine and socio-biological failures are connected, as new machines usually require new organizations and new skills in the humans who use them. The probabilities of initial failures can be quite high until the new skills are developed. This was particularly evident, for example, in the early stages of aviation, or during the initial phases of the Soviet space program that was recklessly accelerated. A recent example of this kind of failure was also the tragic accident that cost the lives of John Kennedy, Jr. and his passengers in their ill-fated flight in July of 1999. Failures also occur, of course, by acts of nature—"acts of God"—that we are unable to predict or prepare for, even though we are making progress on guarding against them, as in the case of floods and earthquakes.

The After-Death

After death what remains of a biological organism is a lifeless body. However, the genes may have been transmitted if the organism has progeny. In advanced animals possibly, and for sure in the society of humans, there remains also the memory of the deceased. The machine, too, leaves physical remains and at times a memory among humans and society. (Thus we like to recollect the history of earlier artifacts.)

Humans seem to be the only living organisms that have a sense of anticipation of death. That predisposition—the unavoidable correlate of an advanced brain—is socially useful in preparing the transition from one generation to the next. With a machine, anticipation of future failure—the functional equivalent of death—could be useful when the machine has to perform critical tasks or operate in extreme environments and needs to transmit information to the operator or to another machine before it fails.[9]

Engineering *versus* Science

The creation of definite performance machines is the domain of engineering, whether carried out by those we label engineers or by others. The engineering process is very closely coupled with science, the quest to understand nature. Simple machines—at first, like early science, the result of intuition, experience and empiricism—led to more complex machines, which embodied the most advanced science available or, as was the case of the clock, artillery, or radio, may have preceded the scientific theories of the time. Complex machines, in turn, make it possible for science to attack ever more complex phenomena. We have reached a stage when not only machines serve as models for the understanding of biology, but in turn, that understanding is becoming a very powerful source of ideas for the creation of machines (e.g., Bugliarello, 1968). The interaction of engineering and science is even closer if we consider that engineers, to carry out their tasks, must endeavor to understand nature, and often act as scientists to acquire the necessary knowledge. They must study a river in order to make it navigable or the phenomenon of electric conduction in order to utilize it. Scientists, in turn, in their quest to understand nature, often need to create artifacts, such as instruments, artificial molecules, or modified genes, and sometimes are called to do the work of engineers, as was the case in the development of nuclear weapons.

Even with these caveats, the differences between science and engineering are fundamental, and are overlooked to our disadvantage. They are differences in purpose, method and responsibility. To reiterate, the purpose of science is understanding; that of engineering is creation—the modification of nature and the creation of something that did not exist naturally. The method of science is building theories about phenomena and verifying their validity; that of engineering revolves around the concept of design, and the related concepts of cost, of effectiveness of the design in achieving an intended goal, and of safety for the engineered artifact's users and the environment.

The responsibility of the scientist is to provide society with the best possible understanding of itself, of its constituents and manifestations, and of the world in which we are immersed, from the smallest particle to the universe. Here again, engineering and science are intertwined. Science needs to be increasingly concerned with a nature now altered by the machine—by the work of the engineer. Engineering, in turn, needs to help science understand the imperatives and complexities of human-made designs, their impacts and the irresistible fascination they hold for humans.

The responsibility of the engineer in modifying nature is to respond to the needs and the will of society. That response is fraught with the moral dilemma of the broader responsibility to our species, as when two societies, each served by its own engineers, clash in war. This is not unlike the dilemma confronting religion in similar circumstances.

Many future advances of engineering will depend ever more on a close interaction with science. At the same time, far more than is the case today, engineering will need to recognize its metabiological nature and base its designs on an understanding of the emotional component of human nature. This is particularly urgent when engineering deals with machines and technologies of broad social impact, such as weapons or genetic engineering, that powerfully affect human emotions. An example are the emotions generated by the death of innocent civilians caused by the permanence of land mines long after a conflict is over. A consciousness of the metabiological nature of engineering can provide more flexibility and imagination in the design of machines, but also serve as a clear reminder that machines are created to enhance biology. They should not oppress or destroy, either deliberately, or because of insufficient attention to their side effects.

CHAPTER 5. TAXONOMIES

There is no single evolutionary principle or agent, as in the case of genes in biology, that could help classify machines in their enormous variety.[10] With biological organisms, taxonomies are of great usefulness in understanding the origin and evolution of the species.[11] Darwin used the metaphor of a tree to convey the branching out of life forms from common origins as they evolved. Today that metaphor tends to be replaced by that of a very convoluted tree rather resembling a net (Doolittle). However, the concept of evolution from one form of life into another and of a common origin for all life forms, even if with complex cross-connections, remains the bedrock of biology.[12] In machines, there is no original nucleus or cell from which everything developed genetically. The ancestor of an airplane is not a bridge, that of a nuclear weapon is not a turbine. Different kinds of machines, like an electric motor, a chemical reactor, or a dam, have no common "genes" or origins other than the evolution of the thoughts and knowledge of their designer. Thus, the development of all machines cannot be represented by a single taxonomic tree, however convoluted, but requires a multitude of trees, each with a different origin (Fig. 15). (The same is true of societal organizations—the other metabiological entities—as I shall discuss later.) For this reason, taxonomies do not receive much attention from machine designers and have been studied more by the historians of engineering (Kranakis, Petroski, Weber).

Given the enormous variety of machines, a comprehensive taxonomy would be a nearly impossible task, as well as a largely futile one from the design viewpoint. Even when there were far fewer types of machines, books on machines, like the famous one by Ramelli in the 1500s, did not attempt a systematic evolutionary classification (Ramelli).

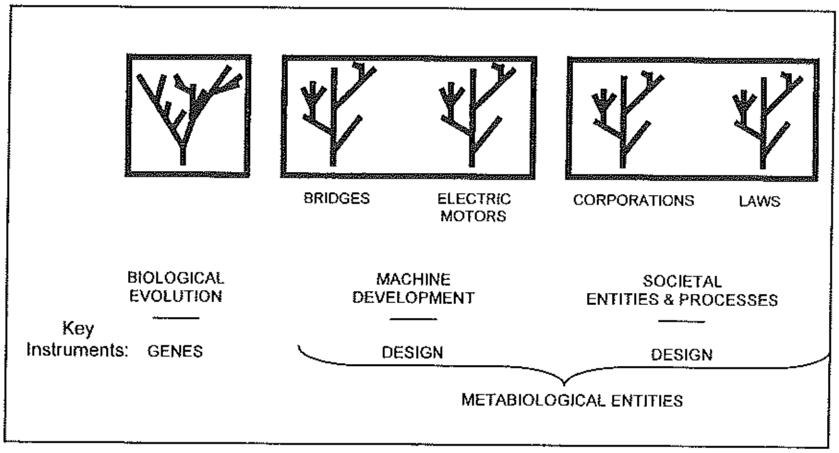

Fig. 15. Biological Organisms and Metabiological Entities

We believe that all biological organisms have a common origin and their evolution can be represented by a single tree, however complex. Metabiological entities (machines and organizations) have multiple origins and cannot be represented by a single tree.

Trees of Machine Development

Yet taxonomic trees for machines can be very useful. The tree for each family of machines helps us understand the demands to which it responds, the inputs of knowledge and resources, the connections to other trees, and the impacts on biology, society and other machines (Fig. 16).

Trees can be drawn for every kind of machine and can branch out and interconnect as a result of technological advances. Machines such as the electric motor, the internal combustion engine, or the computer have evolved continuously and have made possible, in turn, an enormous range of other machines. Taxonomic diagrams also invite speculation as to further advances. What could be the role, for example, in the further evolution of many machines, of self-repair and self-replication, or of the introduction of machine consciousness?

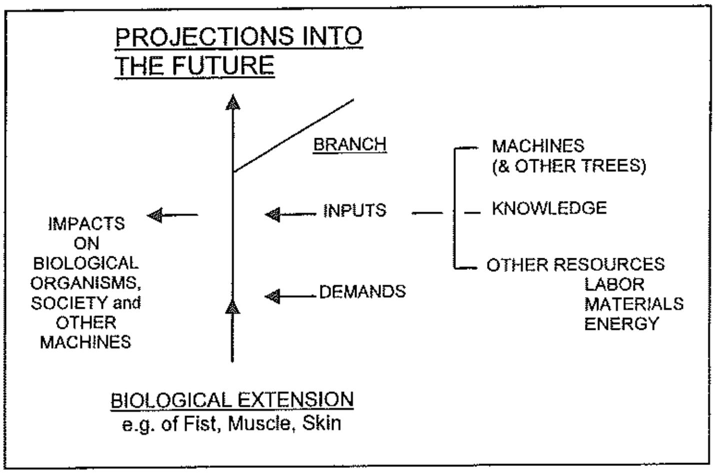

Fig. 16. Paradigm of A Machine "Evolution" Tree

Each tree can be viewed as a metabiological extension of an organ or function (Fig. 17). Machines that extend our fist could start with the simplest percussion machine, a stone in our hand. If we limit ourselves to peaceful applications, we could consider next the hammer and other stone tools. Water power as a fluid energy transformer led to more powerful mechanical hammers; the advent of steam made possible the steam pile driver and the advent of the internal combustion engine led to the compressor and the pneumatic hammer. A new chapter was introduced by the explosive staple or nail gun. Every new power source has led to a different application and a new branch of a taxonomic tree and so have new materials and new information processing capacities (Appendix I).

Similarly, if we focus on houses—extensions of our skin—a taxonomic tree starting with lean-tos and huts would progress to houses, all the way to high-rise buildings[13] (Fig. 18). Advances in high-rise buildings are spurred by the high cost of urban space and hence by the necessity to go vertical. Extremes of temperature and wind have led to the creation of heat and air-conditioning devices, as well as of dynamic anti-vibration balancing devices such as the one on top of the Citicorp Building in New York. Concerns about operating costs and security are the reason for today's "intelligent" buildings. These are all examples of how bio-social demands and scientific and technical knowledge lead to evolution of machines and of how, in turn, new machines lead to new demands.

FIST EXTENSIONS

MACHINE	POWER SOURCE	SUPPLYING DEVICES	KNOWLEDGE BASE
NAIL GUN	EXPLOSIVES		CHEMISTRY
PNEUMATIC HAMMER	COMPRESSED AIR	ENGINES; MOTOR	THERMODYNAMICS; ELECTRODYNAMICS
STEAM PILE DRIVER	STEAM	STEAM ENGINE	THERMODYNAMICS
MECHANICAL PILE DRIVER	BIOLOGICAL (HUMANS & ANIMALS)	PULLEYS; MUSCLE	MECHANICS
HAMMER	HUMAN	MUSCLE	MATERIALS
STONE	HUMAN		

FLUID ENERGY TRANSFORMERS
(MUSCLE EXTENSIONS)

MACHINE	POWER SOURCE	SUPPLYING DEVICES	KNOWLEDGE BASE
LIQUID ROCKET	LIQUID FUEL	PIPE; RESERVOIR	COMBUSTION; THERMODYNAMICS
GAS TURBINE	GAS	PIPE; RESERVOIR	THERMODYNAMICS; GAS DYNAMICS
STEAM TURBINE	STEAM	STEAM ENGINE	THERMODYNAMICS
HYDRAULIC TURBINE	WATER	PIPE; PENSTOCK; DAM	HYDRAULICS
WIND MILL	WIND	TOWER	EXPERIENCE; AERODYNAMICS
WATER WHEEL	WATER	CANAL	EXPERIENCE; HYDRAULICS
SAILS	WIND		EXPERIENCE; AERODYNAMICS

Fig. 17. Examples of Extensions of Our Fist and Our Muscles

Thematic Taxonomies: Materials, Energy, Information and Systems

A set of very useful taxonomies are those based on the key physical or systemic themes that govern the design and operation of machines. For instance, some machines have *materials* as their major theme, as in the case of artifacts of stone, metal, or ceramic; the theme of other machines may be *energy*, from sails, to motors and explosives; and that of other machines yet, from books to computers, is *information*. We can also think of machines in terms of *systems*—of how their components interact and are integrated (Fig. 19).

A thematic classification of this kind can be meaningful not only for machines, but also for the biological and social domains. It enables us to look, for instance, at a biological organism in terms of the materials that constitute it and their properties, such as skin, bones, or blood; in terms of energy processes, from respiration and digestion to energy transformation in the mitochondria; in terms of information processes, from the functioning of the brain to the nervous system, to hormones, to inter- and intra-cellular communications and DNA; or in terms of systems—of how the organism is organized and of how organs interact.

In the societal domain, different historical times have been shaped by different capacities to utilize materials, energy or information. Ancient Egypt, Rome, ancient China or the Incas depended vitally on the ability to build material artifacts such as walls, roads, bridges, or pyramids. The societies of the industrial revolution were shaped by the ability to utilize vast quantities of energy; in our contemporary society, the major theme has become information.

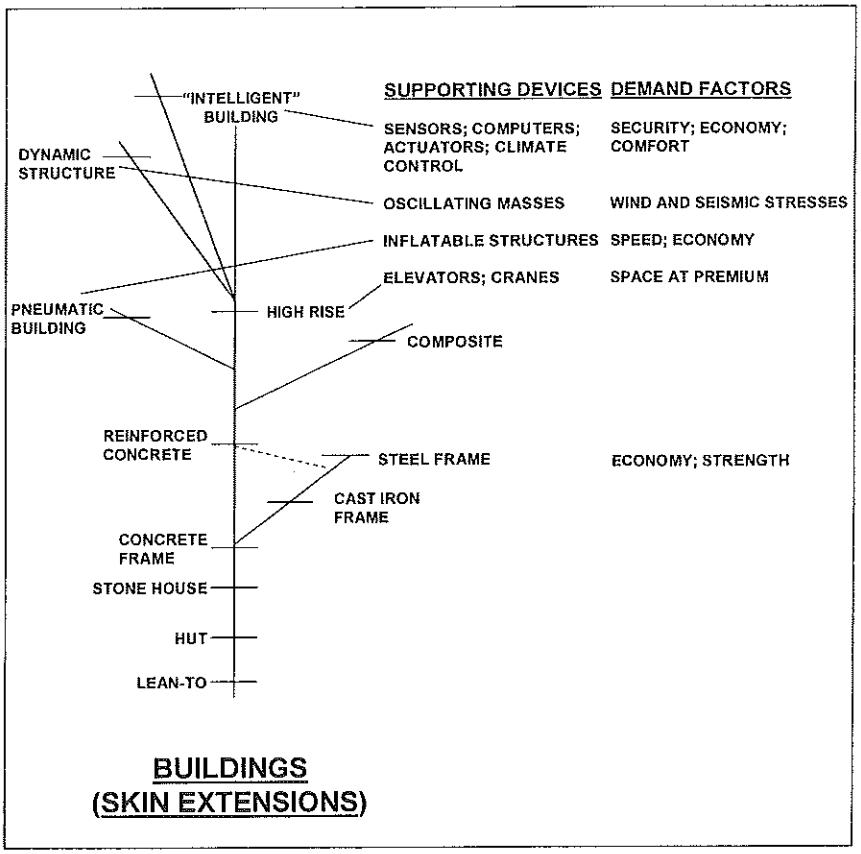

Fig. 18. A Taxonomic Tree for Buildings

	BIO	SO	MA
MATERIALS	CELLULAR SKIN STONES TENDONS		METALS SHAPED CERAMICS PLASTICS ....
ENERGY	MITOCHONDRIA MUSCLES	TEAMS	SOLAR WIND GRAVITATION FOSSIL ELECTRO-MAGNETIC NUCLEAR ....
INFORMATION	DNA HORMONES BRAIN LANGUAGE	MESSENGERS ASSEMBLIES SCHOOLS	SYMBOLS WRITING BOOKS TELEGRAPH COMPUTER ....
SYSTEMS	CELLS ORGANS CIRCULATION ORGANISM ECOLOGY	BUREAUCRACIES LAWS STATES SUPERNATIONAL ENTITIES	CLOCKS ENGINES AIRPLANES ....

Fig. 19 A Set of *Leit Motifs* for Machines, Biological Organisms and Society

The use of biological energy was the first great shaper of human advancement. Until relatively recently in the history of the species, the only major source of energy available to humans, aside from food and fire, were the humans themselves. Human muscles did the work, shaped tools, powered weapons, rowed boats. Human energy continues, of course, to be indispensable. Today, it powers bicycles that are a key form of transportation in many parts of the world and it even succeeded in propelling a flying machine, the *Gossamer Albatross*, across the English Channel on June 12, 1979.

The next major wave in the utilization of biological energy was the combination of biological forms of energy—of humans and animals. This revolutionized agriculture, transportation and war. Cavalry became a fundamental element of military strength; elephants were terrorizing weapons in the armies of Hannibal and Pirrus, and are still being used today in India to do work.

The utilization of animal energy was made possible by machines such as yokes, stirrups and harnesses. The evolution of each of these machines has represented significant steps in human progress and conferred distinct advantages to the societies that invented them (White). The greatest advances in the mastery of energy started with machines that draw energy from the environment. Sails were among the earliest of these "environmental machines," followed by windmills, all the way to water turbines, solar energy collectors, and tidal power plants. Even greater advances have occurred with what can be called "active" machines, made possible by physical or chemical transformations. Active machines, from guns to steam engines, internal combustion engines and nuclear energy, are a development only of the last human millennium, with few exceptions, such as the earlier Chinese invention of gunpowder, or the toy steam engines of Hero of Alexandria.

Throughout history, each step in the progression of materials and energy technology has conferred advantages to the society that mastered it. Thus the wielders of metal weapons defeated those of stone weapons, and titanium-hulled, nuclear-powered submarines far outperform steel-hulled, diesel-powered ones.

Similarly, advances in information and communications beyond messengers and oral messages have been of great significance to human advancement. They have taken many forms:

- from the ability to communicate across time (the book) to real-time communications (the telephone and the radio);
- from passivity, as in the case of the book that can only be read, to interactivity, as in the case, again, of the telephone, the computer or the Internet;
- from territoriality to metaterritoriality that is, from information that could be contained within a territorial realm to information that transcends boundaries, as in the case of radio and television (Bugliarello, Spring 1996);
- from linear processes to concurrent processes, as in the case of the computer, which has made possible airline reservations whereby multiple reservation offices can operate simultaneously on the passenger list of a single flight, or in the case of new research methods, in which several lines of investigation are being pursued concurrently, as in the search for new drugs.

Advances in these capabilities have led to advances in social systems—in the organization of society. But that organization has a dynamic of its own, influenced only in part by the use or evolution of machines. For instance, the rise of Athenian democracy and its eventual lapse into tyranny was largely a social rather than socio-technological phenomenon. What is relevant in our context here are possible analogies in the organization of machines, biological organisms and society. How a biological organism coordinates its functions, is organized to grow, reproduces, repairs itself or responds to outside changes and maintains a stable inner environment invites the emulation of machine designers and societal leaders. The brain challenges the computer designer to create computers with greater flexibility, greater inductive and deductive capacities, greater ability to process visual information and, ultimately, with consciousness. In turn, how a computer is organized helps us ask questions about the brain. In the societal context, bureaucracies have some similarities both to living systems and to systems of machines. They behave, as much as possible, as predictable definite performance entities, but good bureaucracies also endeavor to retain the flexibility of an organism.

The matrix in Fig.19 suggests to us frontiers in every direction. To make just a few examples in the vertical direction, it suggests the potential of transforming our social information mechanisms, such as education, through a closer integration of biological and machine information. A distant frontier, as mentioned earlier, could be the use of mitochondria-like devices for the creation of environment-preserving energy machines operating at room temperature. We are also beginning to see the possibility of opening up a new realm of technological opportunities by intimately merging in the machine domain materials and information, to create "intelligent" materials. In a diagonal direction, as another example, combinations of biological materials and machine-information systems could revolutionize organ replacements.

Individual *versus* Collective Machines

A distinction between machines for individual use and collective machines can help us better understand the interactions of machines with biological and social entities (Fig. 20). Clothing, pills, eyeglasses, watches are examples of machines used exclusively by a single individual; a water-supply system, a highway and infrastructure in general, are collective machines, serving groups of individuals. The automobile falls between the two categories, as at times it is used only by one individual and at times by a group.

Collective machines could be classified according to the social organizations or entities that use them, from families (e.g., houses and fences), to cities (e.g., streets and sewers), states (e.g., intercontinental missiles) and global associations (e.g., the space station or some particle accelerators).

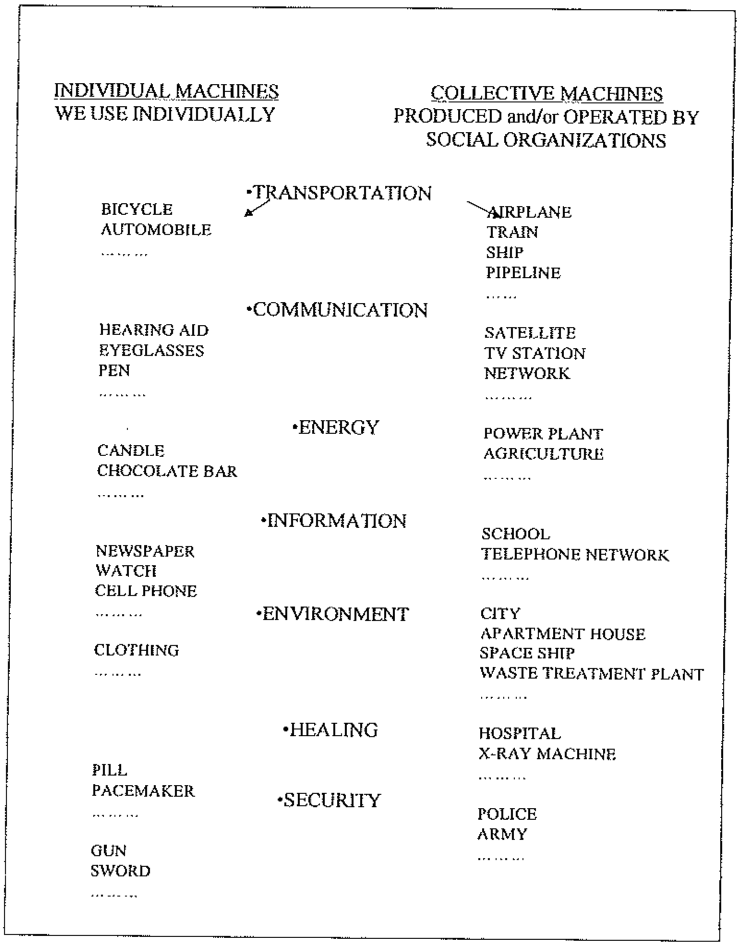

Fig. 20. Individual *versus* Collective Machines

Today, four trends are significant. In the first place, *collective machines depend ever more on complex organizations* to produce and maintain them, as is the case of the airplane or satellite TV. Secondly, however, *individual machines also are increasingly produced and maintained* by complex organizations. This was not the case in the not too distant past of developed nations, when the economy was primarily agrarian and artisan and many individuals were able to produce the machines they used, from clothes to tools and weapons. It continues to be the case for the poorer economies. In the third place, an *increasing number of sophisticated individual machines* produced by those organizations, from pacemakers to implanted lenses and artificial organs, *are now operating inside our body*, contributing to the blurring of the biology-machine boundary. Finally, *the* *development of collective entities,* such as factories, hospitals or transportation systems, is *characterized by ever more intense interactions between their social and machine components.* In hospitals, for instance, medical staffs have become increasingly dependent on advanced medical devices.

The result of these trends is a society in which the individual is enhanced by ever more powerful but also ever more costly and complex machines and processes that the individual cannot build or repair. These machines and processes require sophisticated organizations, over which we as individuals have control only through the collective and imperfect mechanisms of the marketplace, or of the political-legal process.

The dramatic shift in the nature of our individual machines exacerbates our dependence on complex machines and our risk. Should, because of a major catastrophe, all those machines and the organizations that produce or operate them fail, we would find it very difficult, indeed impossible, to survive. In technologically more primitive societies that danger was less serious as those societies were much better able to create personal machines. Today, this is virtually impossible. But even without considering such a dire global scenario, we cannot overlook the fact that *when society disaggregates, collective machines tend to fail and individual machines become more important, but the collective facilities for their production or operation also tend to fail or be diminished.* The disrepair of roads and aqueducts in Europe after the fall of Rome or of the irrigation system in Haiti after the revolution against the French occupation are telling examples.

Medieval European House
14TH-15TH Century

Beds	Stove	Wall hangings
Benches	Fireplace	
Boxes		
Chairs		
Chests		
Credenzas		
Settees		
Shelves		
Stools		
Tables		

Today's House

Beds	Stove	Carpets
Chairs	Oven	Paintings & Framed Pictures
Armchairs	Microwave	Wall Hangings
Consoles	Toaster Oven	Mirrors
Carts	Refrigerator	
Couches	Freezer	Radio
Cupboards	Air Conditioner	Television
Bookcases	Mixer	VCR
Shelves	Toaster	Stereo System
Sideboards	Knife Sharpener	Computer
Floor Lamps	Electric Toothbrush	Telephone
Clocks	Vacuum Cleaner	Alarm System
		....
		....

Fig. 21. Typical Functional Machines in a Medieval European House and in Today's House

Functional *versus* Symbolic Machines

We create machines for either a functional or symbolic purpose. Sticks, weapons, or airplanes have a functional purpose; a necklace a symbolic one. The two purposes can be joined.

Clothing, for instance, combines the functional purpose of protection with the symbolic one of conveying a message about our status or our mood.

We may venture to say that *the more technologically demanding the extension of biology by a machine, the greater is the predominance of the functional over the symbolic.* In an airplane, a gun, a submarine or a space shuttle, the functional is of overwhelming importance. Instead, with the automobile, where technology evolves more slowly, the symbolic function—the automobile as a status symbol—becomes very important. A Honda Civic, a Rolls Royce and a Ferrari are all perfectly functional, but convey different social messages (without prejudging here which is more significant). Historically, some machines created for symbolic purposes have been also at the limit of machine capabilities, as exemplified by the pyramids, the Gothic cathedrals and the great mosques. The house is a multiple-purpose machine. Mumford called it a machine for living (Mumford). It combines the functionality of shelter and comfort with a symbolic function, a role in social interactions. In the typical medieval houses in the West the social function was more important than comfort, which was limited to bare essentials, in contrast to the abundance of functional machines in today's houses (Fig. 21).

Progression in Machine Capabilities—From Passivity to "Consciousness" and Self-Replication (Fig. 22) (Fig. 23)

We can call *passive* a machine that receives inputs from the outside that are not transformed *purposefully* within the machine. Thus, a hammer receives energy from the hand of the user, and transmits it to an outside object, the nail. (Of course, any mechanical machine, even a passive one, transforms energy and exchanges information internally,[14] but that is not its *raison d'être*). In the information domain, a book is a passive machine, while a computer is not, because it transforms purposefully the inputs—the information—it receives. A dam, a highway, a bridge, or other structures that modify the environment also are usually passive, even if they can be very sophisticated in their design. They perform statically, in spite of controlling or enhancing a dynamic

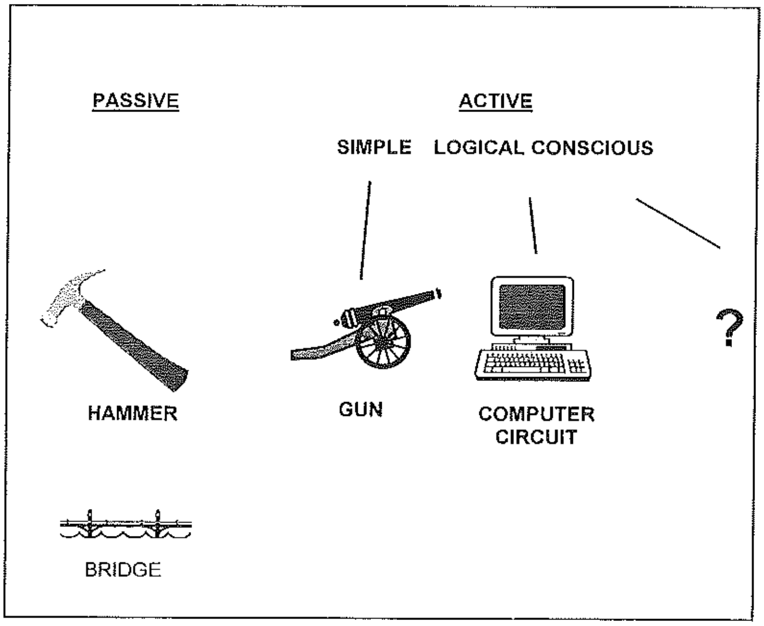

Fig. 22. The Spectrum of Machine Capabilities

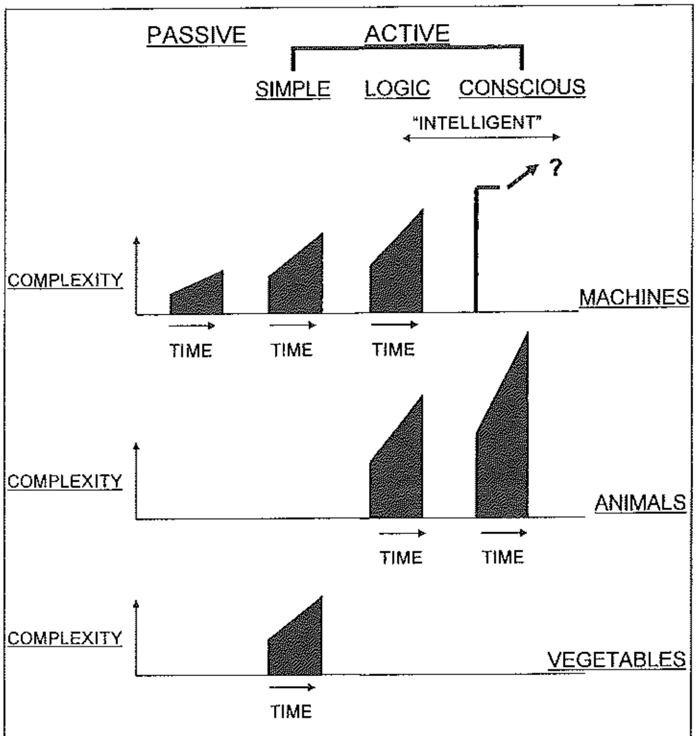

Fig. 23. Complexity in the Spectrum From Passive to Conscious

phenomenon, such as water flow or traffic.

The next conceptual step in machine evolution beyond static machines are passive machines with moving parts. How difficult the achievement of such a step was is underscored by how late in human evolution simple moving machines like the wheel or the spindle came into being, and how a civilization like that of the Incas never used the wheel for transportation. However, like the hammer, both the wheel and the spindle are still passive mach-ines.

Active machines, conversely, are purposefully designed to transform or process internally their inputs, be they energy or information. They can be categorized in a variety of ways, from the simplest to the more complex. A *simple active machine* is one that transforms only energy. An example is the gun, which receives energy from the outside (the gunpowder), and transforms it internally. Other examples range from internal combustion engines to nuclear weapons.

Feedback that enables a machine to regulate or correct its own output represents a higher level in the capabilities of active machines. Simple examples are the Watt regulator invented over two centuries ago to control the speed of engines and the thermostat invented at the end of the nineteenth century. (A vegetable is, in this, analogous to a simple action machine with feedback in the sense, and only in the sense, that it is endowed with feedback but not with the logic of an advanced machine.)

Yet further steps toward increasing capabilities are machines that can foresee the conditions they will encounter and can adapt accordingly—for example airplanes with radar to scan the weather ahead.

Active machines endowed with sensors and with the ability to process by means of a logical algorithm the information, the inputs, they receive from the environment can be called *logic machines*. An example is the computer, which receives its input from the outside and manipulates it internally.

The highest level of complexity among active machines is that of *conscious machines*—at best only a dream today because we do not quite understand what consciousness means. These are machines endowed with a sense of self and able to integrate their multiple capabilities. By using logics and memories of previous interactions they will respond flexibly and with judgment to the environment perceived through their sensors, and of which they build internally a model.[15]

There is nothing in principle, I believe, that says that a machine responding in some degree to these requirements could not be designed. In a limited mechanistic context, consciousness could also be viewed in terms of error control. While an unconscious response to a situation is fast and can be "hard-wired" both in a biological organism and a machine, a conscious response is far more complex. It must be defined, analyzed and combined with value judgments as to the nature of the potential error that needs to be controlled. Much of the ability to respond is based on learning, and requires the flexibility of software. Viewed in these terms and considering our rapid advances in computer science and engineering, we can certainly conceive of embedding in a machine some elements of consciousness.

Conscious machines would differ fundamentally from logic ones in this sense: while the reaction of a purely logic machine to an external situation is totally predictable in principle, that of a conscious machine is not. Thus a conscious machine brings machines closer to the semi-definite performance of biological organisms. The question is: to what advantage? The importance of providing some advanced machines with consciousness is that consciousness is the base of common sense, the ability to judge the truth and to understand. In certain circumstances, all these could be useful attributes, for instance, in a machine for the exploration of space. Consciousness is not needed when a process is automatic or follows rigidly rules as they are programmed (Penrose). Because we demand absolute consistency and predictability of most of our machines, it is clear that even if it were possible, it is by no means desirable to provide most machines with consciousness.

Between the logic and the conscious machines, we could place the vaguer concept of *intelligent machines*, machines which partake, in varying degrees, of the characteristics of both. They have memory and logical decision powers, however these may be provided. None of today's "intelligent" devices, however, has even a glimmer of what consciousness is. They are rigid, and devoid of what, for lack of a better term, we could call humanity—of emotions and of the ability to respond to them.

Conscious machines are truly a frontier of machine development (bio-machines are another). That frontier still eludes us, just as a full understanding of what consciousness is eludes biology. But there is no reason to believe that we will not be able to create machines with substantial learning capacity, with the ability to form concepts and with some kind of autobiographic sense, coupled with the ability of repairing and altering themselves, to self-assemble and self-reproduce.

By way of summary, we could plot the degree of complexity of machines, from passive to conscious ones *versus* the progression from instinctive to engineered machines (Fig. 23), and extend the plot to a third dimension representing the ability to self-repair or self-replicate (Fig. 24). In the plot:

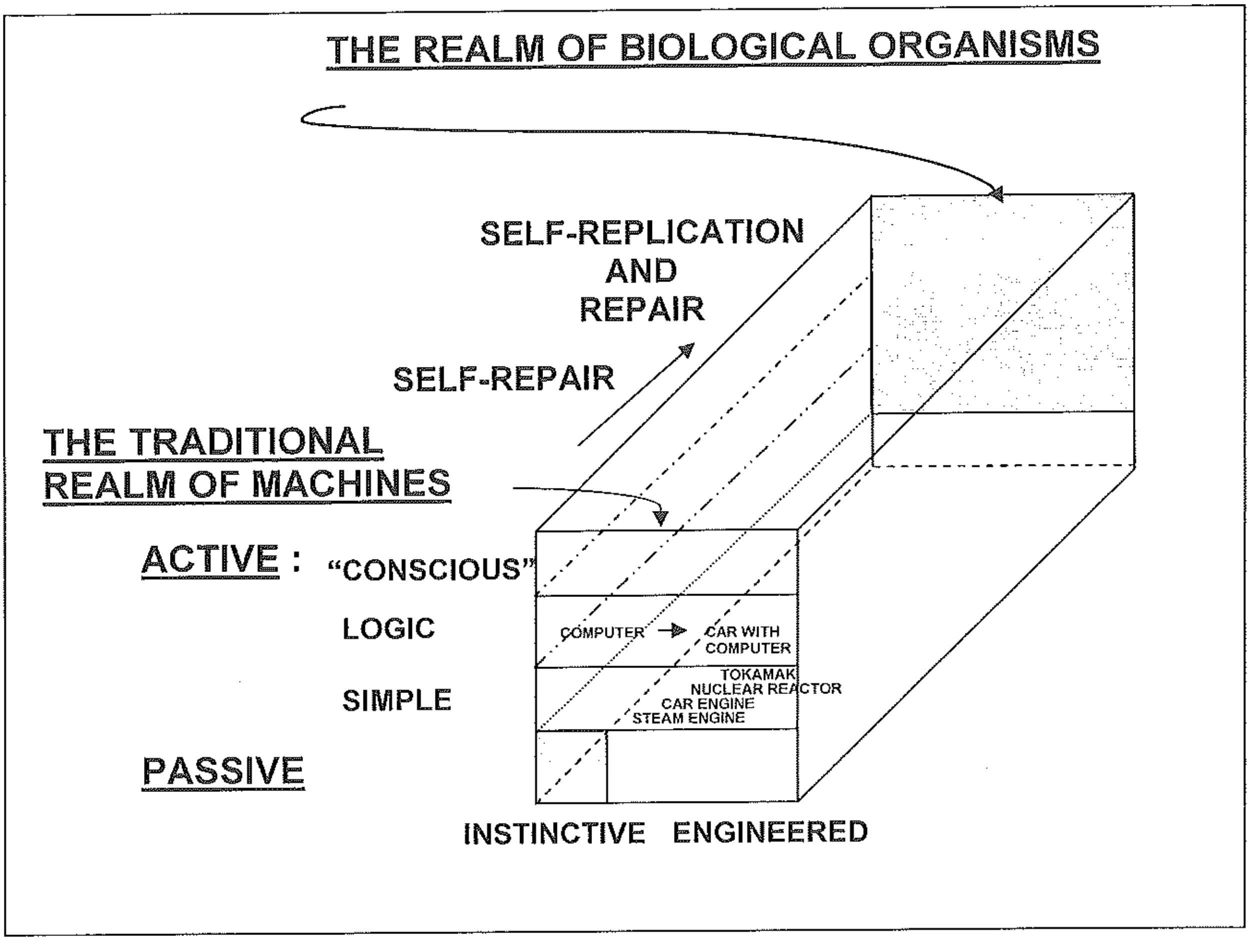

Fig. 24. Machine and Biological Realms
A Three-dimensional Plot of Capabilities

- The only instinctive machines are passive ones.
- The progression from the steam engines of the Industrial Revolution to the internal combustion engines to nuclear reactors has been one in the direction of very complex engineering. Yet these all fall in the category of simple machines, except for some forays into the domain of logic components used to monitor and control their operation, as in the case of the growing number of computers in automobiles.
- The progression from passive to active machines of increasing complexity proceeds diagonally across the front plane of the diagram in Fig. 22. An example in the area of materials is the progression from inactive materials to "intelligent" materials endowed with sensing or computing abilities.
- Today, our machines fall still on the front plane of the figure. Their design has not progressed toward the third dimension of self-repair and self-replication. Some forays, however, have occurred in the self-replicating domain with logical machines, such as computer viruses, and in the self-repair domain with chemically active machines. An early example of self-repair were the self-sealing fuel tanks introduced in combat airplanes during World War II.
- Biological organisms, on the other hand, fall all on the self-replication plane at

the rear and encompass in their domains the entire range from logics to consciousness.

Feelings and the Machine

An intriguing question connected to that of consciousness is whether it is possible to design a machine that has feelings. We as humans have feelings, and so has a society. In some limited sense, something equivalent to a sense of feelings can be built in a complex machine. For instance, it can be provided with some elements of intelligence and imagination, a capacity for recognition and a sense of gratification for certain interactions. But what for? Is it *desirable* for the machine to have feelings? The answer, again, is yes, when the machine is carrying out what otherwise would be a human function—such as screening phone calls, or, in the case of a domestic robot, caring for its masters.

Biomimesis and Bio-machines

If we seek to bring machines closer in their capabilities to biological organisms, we can follow two paths. The first, a kind of reverse engineering, is to create *biomimetic machines* designed to imitate capabilities or features of living systems. I discussed earlier, for example, the inspiration that engineers can draw from proteins. But biomimesis is still in its infancy. Although we do not know yet how far we can proceed on that path, it is intriguing to consider some examples of the potential of *biomimesis design* (Fig. 25):

Multi-functionality—the ability of a machine or machine component to perform several functions—is exemplified by our skin. The skin contains our body, is endowed with sensors, is permeable outwardly, as we perspire, as well as inwardly, it cools us and also has, or we have endowed it with, an aesthetic function. Self-reproduction is a major design frontier which, as I have discussed, has been achieved thus far in machines only in a very limited context. Integration, encountered in electronic integrated circuits, is still, by and large, very limited in machines in comparison to how universally and intimately it occurs in biological organisms.

Adhesion in biological organisms affixes muscles to bones. As a way to hold together machine components, rather than bolting, welding or soldering, it is used in some glued structures. But these are still only timid applications.

Development of energetic processes at normal temperatures and pressures by chemical rather than the thermo-mechanical approaches widely used today in the generation of power would be extremely desirable. So would the ability to dispose of and recycle machines and their waste products through metabolic processes.

Providing some machines with some degree of consciousness or, given our still very limited understanding of that faculty, at least with some serious decision-making capabilities, would help increase their versatility and improve the human-machine interface.

A distant biomimesis frontier is the development of what can be called "flow construction." Cellular biological organisms are created by a process of constant expansion from an original single cell, which gives rise to the extreme complexity of an advanced organism. Although enormously difficult, it is conceivable that we could build a machine by a logistic planning of the flow through a self-expanding and branching pipeline conveying elements of the machine to be constructed. The elements could then further migrate and be transformed through a diffusion process, using catalysts or thermal agents to create preferential strengths, conductivities, etc.

The other path for bringing machines closer to biological organisms—or *vice versa*—is the creation of *bio-machines*. These are intimate combinations of machines and biological organisms that partake of the advantages of both. In their extreme form, bio-machines would make it impossible for us to decide, to the further desperation of philosophers, whether they are enhanced biological organisms or enhanced machines.

A simple example of an entity partly biological and partly artificial is hybrid instrumentation combining a biological sensor, such as an enzyme, and an electronic platform that magnifies and processes the information received from the enzyme. Another example are machines that operate inside a biological organism, such as an artificial organ, a chip implanted in a region of the brain, a drug, or an engineered gene. A still highly hypothetical example could be an energy machine utilizing the cell's mitochondria, to produce energy at room temperature without environmental injury. Ultimately, bio-machines could be viewed, in humans, as leading to a Zen-like merger of the artifact and its maker (Bugliarello, 1989). How far we are yet from our ability to achieve this, should we want to, is exemplified by the difficulties in achieving communication between a medical prosthesis and organs of the body—to transmit, for example, the message that the

"DESIGN" GOALS	BIOLOGICAL EXAMPLES	MACHINE
• MULTIFUNCTIONALITY	SKIN	ACTIVE SURFACES (c-f)
• SELF-REPAIR	SKIN	SELF-SEALING TANKS (c)
• SELF-REPRODUCTION	ALL ORGANISMS	COMPUTER VIRUSES (c) SELF-REPRODUCING MACHINES (f)
• INTEGRATION	AT CELLULAR LEVEL AT ORGANISM LEVEL	INTEGRATED CIRCUITS (c)
• ADHESION	MUSCLE-BONE	GLUED STRUCTURES (c) GLUED MECHANICAL MACHINES GLUED SHIPS (c-f)
• WASTE PROCESSING RECYCLABILITY	METABOLISM	SOME LIMITED RECYCLING (c)
• ENERGETIC PROCESSES AT NORMAL TEMP. & PRESSURE	MITOCHONDRIA DIGESTION RESPIRATION	(f)
• LEARNING	BRAIN	ADAPTIVE PROGRAMMING (c)
• "FLOW CONSTRUCTION"	ALL ORGANISMS	"FLOW CONSTRUCTION" (f)
• SOME ELEMENTS OF CONSCIOUSNESS	BRAIN ("MIND")	(f)

c: *current;* f: *future*

Fig. 25. Examples of Biomimesis
(A Kind of Reverse Engineering!)

prosthesis is there to help and should not be rejected.

Clearly, biomachines confront our society with enormous moral implications (Maguire and McGee). But, aside from those implications, bio-machines present a set of extreme design challenges which, if successfully met, will represent a quantum leap in the evolution of machines [Appendix II]. They range from achieving compatibility and communication between the biological and machine components, to endowing the machine component with the ability to keep pace with the growth and transformation of its symbiotic biological counterpart. The goal is not anymore to attempt to mimic in the machine component the biological component, but to better enhance the machine's capability to intimately connect with the biological organism, in order to produce a new entity combining the advantages of both. One of the greatest difficulties we encounter today in the kind of bio-machine integration represented by artificial organs is that the machine finds itself in a hostile or at best unsupportive environment, while the biological component that interacts with it has the support of the entire organism in carrying out its function, as when it repairs itself. The machine component is isolated. Finding ways to reduce that isolation is essential. (This is almost a vicious circle, because in order to achieve that integration, the machine also must be able to self-repair, etc.)

The difficulties to be overcome in creating complex bio-machines, although enormous, are not necessarily insurmountable. For instance, we can conceive of a bio-machine possessing an autobiographical consciousness arising from its interactions with its biological milieu. In due time, some of these bio-machine capabilities, as they become better developed and understood, could also be transferred to pure machines.

Looking ahead and mindful of our experiences with unintended consequences, we cannot assess which of the two trends—biomimetic machines or biomachines—is likely to have the greatest impact on our future. Probably there will be a blend of the two. It is also probable that the future progression of machines will endow them, beyond today's memory capabilities, with biomimetic intelligence capabilities such as curiosity, an analytic capacity based on logic, a synthetic capacity based on an associative memory and on the inputs from a variety of sensors, and ultimately with some form of judgment and consciousness. All these capabilities, although still remote from practical realization, can be explored in principle. By so doing we can also hope to understand them better in the biological context.

To reiterate, the essential question for society is to decide whether these capabilities are desirable, and if so, in what context. For instance, a certain amount of judgment is probably desirable in most advanced machines as long as it is agreed upon by society, and contained within societally wished-for limits. After all, animals are endowed with the ability to optimize their actions, whether in the quest for food or in defense. There is no reason why similar capabilities would not be useful to us in many a machine. It would be in everybody's interest, for example, to enable a car to override reckless driving, provided, of course, the car's judgment and the corresponding action were reliable.

CHAPTER 6. MACHINES AND SOCIETY

Social organizations and processes are the other great metacorporeal extension of biology, one that preceded the emergence of the machine. Society, like machines, was not consciously invented, but evolved outside of our own bodies, as an extracorporeal expression of our genes. A billion years ago, our genes coagulated into cooperative teams (Ridley). Aggregations of cells made specialization of functions possible, and, in more advanced states, controllable internal environments, which led to ever more complex organisms. It is very difficult to determine when in the course of evolution the external ties between organisms arose that are the foundations of social organizations, from the simplest to the most complex. The society of ants is some one hundred million years old; human societies, of course, are much more recent and conceptions about society are no more than a few thousand years old. Organisms operating in societies rather than in isolation seem to enjoy an obvious competitive advantage, as when lions or wolves band together to chase their prey. That advantage is greatly reinforced by the use of machines.

Society implies communication of some sort, a process that in humans is immensely enhanced by language, which might have emerged gradually as we evolved, but accelerated in the last 100,000–60,000 years (Givon and Malle, 2003). In humans the development of societies has been tightly interwoven with that of machines. This has occurred also with some other biological organisms, such as the ants and the bees with their anthills and beehives, both sophisticated kinds of machines. But only among us humans, with our intellectual capacity, has the abstract concept of organization emerged and evolved. It has become the conscious instrument to help us create complex machines and, through them, ever more complex social organizations.

The interaction society-machines is shaped by the fact that, like its underlying biological organisms, but unlike a machine, a social organization or process is a semi-definite performance entity. Some of its aspects are quantifiable and predictable by means, for example, of demographic or economic statistics, but other aspects, like ideologies or the dynamics of popular mood, are not.

The immense gamut of machine-society interactions is characterized by issues analogous to those in the interaction of machines and biology. Machines extend the power of society in peace and war and help regularize the performance of societal entities, be it through the discipline required in an assembly line or the precision required by an airline reservation system. Machines also complement or replace social entities, as in the case of an automatic teller machine, or of an electronic stock exchange like NASDAQ, but frustrate us when they provide an inflexible response to our needs. Much more rare in today's economic climate, and almost regarded as reactionary, is the replacement of machines with people. Yet, during the 1930s Depression, Milton Hershey refused to use tractors to replace workers and the Germans kept to a minimum the use of mechanical equipment in building the autobahns.

As in the case of machines, and unlike that of biological organisms, it is impossible to reduce the evolution of society to a single taxonomic tree rooted in an original concept from which all societies have evolved (Fig. 15). It is, however, possible to create separate trees that show the evolution of aspects of society, from family to government, or from the partial Athenian democracy, with its census, sex and birthplace exclusions, to today's universal democracies. Other trees may show the evolution of

TECHNOLOGY	APPLICATIONS	REVOLUTIONARY SOCIETAL IMPACTS
•Fire	•Cooking; heating; manufacturing	• Wider range of nutrition & shelter opportunities; new products
•Agriculture	•Planting as an artifact	• Food supply
•Materials	•Ceramics, copper, bronze, iron	• Armies and empires
•Urbanization	•Water supply; housing; walls; transportation	• Cities
•Writing; Printing		• Communications; Reformation; revolutions
•Boats, Sail	•Shipbuilding; sails	• Trade; warfare; discoveries
•Animal harnessing	•Carts, chariots, cavalry	• Energy supply; trade; warfare
•Gunpowder	•Fire arms	• End of feudal society
•Scientific navigation		• Discoveries
•Printing press	•Books	• Diffusion & democratization of knowledge
•Steam engine	•Factories, steamships, railroads	• Industrial Revolution; warfare; railroads
•Water purification & wastewater treatment	•Improved urban water supplies	• Decline in mortality; population explosion
•Electricity	•Lighting, power	• Living & work habits; dependence on networks
•Internal combustion engine	•Automobile, aviation	• Suburb; world community; warfare
•Telegraph, telephone, computer	•Information transmission, storage & manipulation	• Work organization; social habits
•Genetic engineering	•Drugs, therapies	• New medicine, new organisms, human cloning; more food

Fig. 26. Examples of Societal Revolutions Caused by Machines

military organizations, of manufacturing organizations from the artisan's shop to the factory, of commercial organizations, of insurance and stock exchanges, and so on. A chronological tree for the development of trade would start, for instance, with the onset of human trade, believed to have occurred some two hundred thousand years ago, after millions of years of our primeval hunting-gathering. That onset was followed some sixty thousand years ago, in the upper Paleolithic revolution, by significant increases in trading distances, with goods found at distances more than a day's walk from where they were manufactured. Some thirty thousand years ago there emerged the creation of villages and the specialization of trade, shown by pierced seashells carried hundreds of miles inland (Ridley). Usually, all these developments, and particularly those that have followed them to our days, are, however, not linear, so that a tree portraying them would have many branches.

Comprehensive evolutionary trees could be drawn to connect the evolution of a biological organism and that of its metabiological extensions—whether machines or social entities. The trees would start with genes, chromosomes, cells, organisms and extend, extracorporeally, both to society and machines. Trees for different social entities or processes help to underscore interconnections and influences between its elements. For instance, trade has an impact on military organizations that must find ways to defend a trade route, as in the wars that in the first century B.C.E. Pompeii in Rome fought against the Mediterranean pirates, or as in today's protection of oil supplies in the Persian Gulf.

Every significant machine invention brings about changes in society. Major machine inventions have revolutionized human history (Fig. 26), and will continue to do so. Firearms destroyed chivalric warfare in Europe and, with it, medieval society; steam ushered in the Industrial Revolution; the automobile created the suburbs; radio was a powerful instrument for the political emancipation of women in America by enabling them to follow news from the home; the airplane has shrunk distances and made the Earth a very small planet; and the telephone and the Internet have changed our work and social habits and connected us globally. The population explosion, caused by improvements in food supplies and sanitation, is another example of the impact on society of advances in machines.

Usually, however, society is slow to respond to machine innovations. The societal entity that responds faster and more intelligently has the advantage. Thus, the West after the 1500s had the advantage over the Ottomans and Imperial China and, recently, several nimble software companies over IBM.

Significant changes in society affect, in turn, the way in which machines are produced, operated and maintained. The American and the French Revolutions, by democratizing society, eventually enhanced the production of machines by opening up society to the opportunities offered by the Industrial Revolution. The societal impacts on machines are also clear if one looks at the better performance in the production of machines by market economies *versus* centralized economies, or at the influence of different societal attitudes toward risk on the way machines are operated. Examples are the greater risks taken initially by the Soviet space program and, even today, the different risks in the operations of different national airlines. The decay of Roman roads and aqueducts, once the cohesion of the Roman state vanished, is one of the clearest examples of how societal changes affect the way in which machines are maintained. For this reason, today we are concerned about the integrity of nuclear waste repositories: will our society be able to maintain its commitment to guarding and protecting them far into the future?

In the interaction of machines with society, the machine complements society by its power, speed, economy, reliability and durability. Society, however, must use machines with intelligence, flexibility and humanity—all attributes particularly important because the machine, at least as of today, is rigid and insensitive, as so brilliantly portrayed by Charlie Chaplin in the classic film *Modern Times*.

Usually a new machine must operate at first in an existing social framework, as was the case of the tank in World War I. (The military environment often shows some of the most dramatic examples of the consequences of different patterns of socio-machine interactions.) Only later, new social frameworks are created to take full advantage of the potential of the machine, such as the creation of a separate military organization—the armored–division or the air force, or the intelligent store, or home shopping. New machines also influence morals (e.g., contraceptives) and promote new fashions (e.g., pants för early women bicyclists). The two diagrams in Fig. 27 summarize these trends. Eventually, new machines In new social frameworks lead to the creation of even newer machines, which start the cycle again. Of course, new social frameworks may be created even if the machines available to them are old machines and have not changed, but this condition, as in the case of the French and American Revolutions, eventually encourages the creation of new machines.

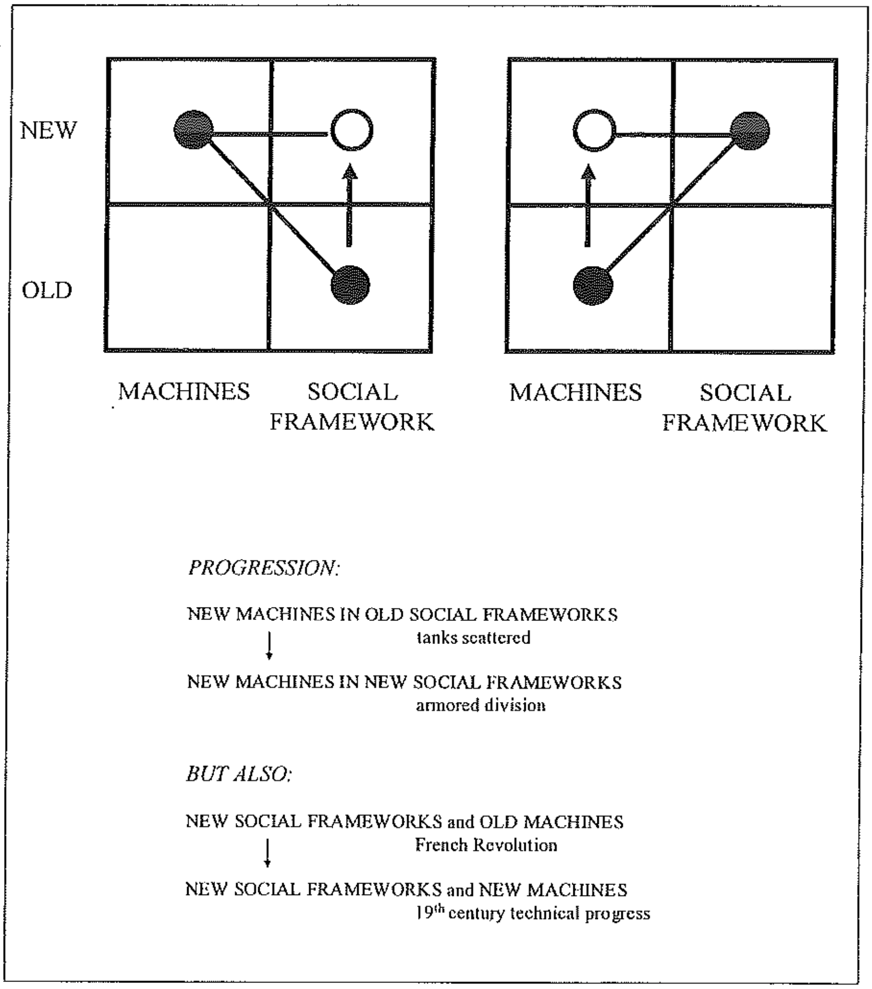

Fig. 27. Machines and Social Frameworks

Part II

THE BIOSOMA

CHAPTER 7. THE BIO-SOCIO-MACHINE SYNTHESIS (THE BIOSOMA)

The interactions of machines with biological organisms and of machines with society cannot be viewed independently of each other. Lorenz showed that animal and human behavior must be considered as a system (Lorenz). That conception needs to be expanded to include machines. For us humans and for a few other species, like the ants, biology, society and machines have come to form the indissoluble whole I have called the *biosoma.*[16] Without machines we would not have much of a chance to survive as individuals or as a society. Conversely, without an organized society, the complex machines which are the product of our brain and support our way of life—indeed our very life—could not be created. Consciousness of the importance of the interaction of individuals, society and machines is certainly not new. Already, the Greeks conceived their theater architecture as having people as an integral part of the design (Malecha). But today, with the extraordinary power and complexity of machines and society, we need to consider that interaction in much greater depth if we are to contemplate a road map of future possibilities for our species.

An Individual's Biosoma

Each individual has his or her own biosoma, which interacts with that of other individuals. We can imagine the biosoma of an individual—say A—as having as its center *the individual*—a biological organism—surrounded by the societal entities and the machines that relate to him or to her, as well as by the environment (Fig. 28). The commonwealth of a society is the ensemble of all the individuals with their individual machines, plus their collective machines and social institutions. In more detail, the individual biosoma is constituted by the individual, surrounded by:

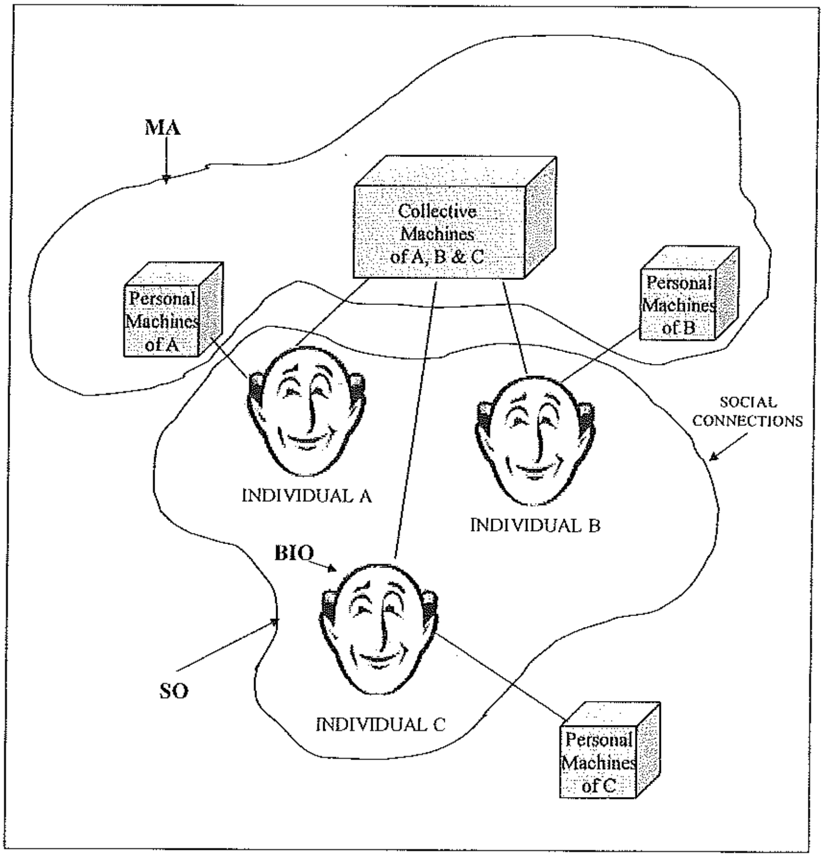

Fig. 28. The Biosoma of An Individual — A Representation

- personal, *individual machines*, from clothes to eyeglasses
- *individual social connections*, from one's family to one's boss—that its other individuals, each in turn with their own biosoma (Fig. 29)
- *collective machines*, that is machines and systems the individual shares with others in his use, such as telephones networks, factories and highways and
- *collective social connections*, such as state, firm, school, church or the law

The relations among individuals have been of concern to society since the earliest civilization, as exemplified by the Babylonian codes. But the relations between individuals and machines have been codified only to a very limited extent, yet they are of growing importance, as I shall discuss later in the context of the essential biosoma. Clearly, the life of an individual is affected biologically, socially and psychologically by his or her individual machines, from clothing to medicine, books and automobiles, as well as by the machines of other individuals, such as the gun of a robber.

Collective machines affect the life of an individual and of social entities, from families to the society of nations. Buildings, vehicles, weapons, factories influence how we work, what and when we eat, how we entertain ourselves, how we fight, and how we find shelter. When society is disrupted or breaks up, collective machines tend to fail. Individual machines then become more important, but the facilities for their production may also fail, as they too are increasingly dependent on collective machines and organizations.

The balance between individual and collective machines is subsumed by that between individual good and public good. When collective machines are too powerful, they help whoever controls them to dominate the individual.

<u>In general, the biosoma of an individual consists of:</u>

The individual + individual machines + individual social connections + collective machines + collective social institutions

<u>Example, for a society of three individuals:</u>

Individual *A* + individual machines + individual social connections to *A* and *B* + collective machines + collective social institutions (serving A, B, C)

Individual *B* + individual machines + individual social connections to *A* and *C* + collective machines + collective social institutions

Individual *C* + individual machines + individual social connections to *A* and *B* + collective machines + collective social institutions

Fig. 29. An Individual's Biosoma

Conversely, when individual machines are too powerful and more influential than collective machines, social disaggregation and anarchy may result. Today, in spite of greater emphasis on individual possessions and on distributed systems of machines, the balance is tipping toward collective machines because, increasingly, individual machines are produced by them and depend on them, e.g. on the Internet, for their operation.

Human Biosoma Periods

One could identify many phases in the interaction of biological organisms, society and machines since the emergence of life. If we focus on the human biosoma, we could, in a very simplified outline, single out five (Fig. 30).

(a) The Pre-Biosoma (approximately until six million years ago)

This period is purely bio-social, as, there are no machines. It starts with the origin of life and extends to our emergence as a distinct biological entity some six million years ago.

(b) The Primeval Biosoma (approximately six million to 10,000 years ago)

During the first phase of the human biosoma, we created the machines and social structures that enabled us to emerge from the forest. Our first steps are still very dimly perceived, but were dramatic. They separated us from the other apes, who lived in the forest, and they launched us on the road of dependence on artifacts—on technology.

Chased away from the forest or voluntary exiles, we started creating with our hands what we needed in our new way of life. We learned for instance to develop clothing, not as much to cover our nakedness as to protect us from the elements or to have pouches to carry food, now that the forest no longer sheltered us and we had to travel longer distances to find nourishment. As we created artifacts, we also learned procedures that extended the range of our physiological abilities. Thus we began to shape our society progressively differentiating it from that of our non-human ancestors. This helped us, in turn, to develop a powerful means of communications and language, which might have emerged from pre-languages relatively recently, some 100,000-60,000 years ago. Clothing, snares, the ability to utilize and, eventually, make fires, the construction of simple shelters and the beginning of weapons and tools, are all of this phase.

In this simplified outline, it is appropriate to extend this earliest phase of the biosoma all the way to the emergence of agriculture and urban settlements about ten thousand years ago–some two thousand years after the last glacial age–because until that time the complexity of machines and of social organisms that man could create as a nomad was by necessity very limited.

For most of the immense period of time of this primeval biosoma, we continued to

<u>YEARS AGO</u>	PRE-BIOSOMA	<u>Bio-social</u>
> six million		
six million-10,000	PRIMEVAL BIOSOMA • Machines (tools), social structures and biological evolution that enabled us to emerge from forest and develop language	<u>concurrent evolution</u>
10,000-500	PALEOBIOSOMA •Agriculture •complex organizations, religions, universities •writing, astronomy •machines for long distance travel (ships, carriages) •materials (shaped stone, ceramics, metals) •harnesses & stirrups •social extension of human muscle •limited individual possessions •aristocratic power	<u>machine as social enabler</u>
600– Middle of 20th century	MESOBIOSOMA • great development of active machines (guns, movable type, steam) • instant telecommunication • control of infections	<u>machine as social leveler</u>
Middle of 20th century–	CONTEMPORARY BIOSOMA •Hyperexplosives (nuclear weapons) •genetic engineering •artificial satellites •exploration of space with spaceships •the information society •consumerism •power of collective machines •high population; urbanization; megacities •the delicate balance escape Earth — destruction of life diversity modify life bio-machines — potential destruction of all life	<u>balance between triumph and tragedy</u>

Fig. 30. Biosoma Periods

evolve biologically. Thus, this was mostly a period of concurrent evolutions of all the three components of the biosoma. Our last mutation occurred some 50,000 years ago. From that time our biological organism has remained unchanged, while many other species have mutated or disappeared, often because of our influence.

(c) The Paleobiosoma (10,000 to 500 years ago)

After the long period of the primeval biosoma, a new phase began, which from ten millennia ago reached all the way to the beginning of the European Renaissance in the 15th century.

In this phase, we learned to develop agriculture and to domesticate animals, to build houses, and to create complex social organizations—cities, states and empires, as well as religions and legal codes. We also learned to construct machines, from ships to carts and roads, that could convey us over long distances over land and at sea. Later in that period, we became increasingly skilled in metals and, through the more sophisticated harnesses and the stirrup, we learned to better utilize domestic animals. And we saw a great flourishing of our artistic abilities and the emergence of religions and knowledge institutions.

During the primeval biosoma, when we were still largely evolving biologically, we did not attempt to control nature, but only to utilize it, by breaking away from the bonds that limited all other living organisms. The paleobiosoma saw us, instead, biologically stable, and dominating more and more both the environment and our own nature. On the surface, our advances were perhaps more dramatic in the social than in the machine domain. Yet, this is also the period of the great material machines. Pyramids, highways, aqueducts, harbors, temples, houses, swords and shields were all machines created by the utilization and working of materials—stone, wood and metals. Many of these machines could be viewed as extensions of our skins. Other machines of this period, such as the bow, the catapult, the sail or the harness, extended our muscles. But the more spectacular extensions of our muscles, those that made pyramids and empires possible, were achieved through social devices, through the collectivization of human effort in the great building gangs, in the phalanx and the legion.

Even today, in regions of extreme poverty, the biosoma reverts to social extensions of man's muscles which were characteristics of the paleobiosoma. The construction of roads, canals and dams in mainland China after the Maoist revolution was often carried out with the most rudimentary machines by extremely large labor gangs. It was not unusual to see a hundred thousand workers on a project, just as was done in the building of the Great Wall of China thousands of years earlier. A few hundred workers suffice today to do the same job, if their muscles are multiplied by powerful machines.

A social, rather than a machine extension of man's muscles tends to reduce the independence of the individual. In the phalanx or in the construction gang what is extended is the power of the leader. Only in social structures in which the participants agree and are fully informed, can a social extension of man's muscle also be viewed by a worker or a soldier as their personal extension. Thus, by and large, the muscle extensions of the paleobiosoma were aristocratic. Only in some of the cities of ancient Greece and with the emergence of the independent city-states in Europe in the second half of the Middle Ages did they become less so.

The paleobiosoma also saw the development of machines and processes, from writing to astronomic instruments, that extended man's mind and senses. Once again, these extensions were essentially aristocratic, the instruments and the province of the few, even if they had impact on everybody.

Throughout this period, individual possessions remained extremely limited for most. As noted earlier (Fig. 21) pieces of furniture and household implements–even spoons–were so few, that they were bequeathed as highly prized possessions.

(d) The Mesobiosoma (600 years ago to the middle of the 20th century)

In the second half of the second millennium C.E., with the use of gunpowder (discovered earlier by the Chinese), of movable type and the clock, and with the intellectual and social developments of the Renaissance, we entered a new biosoma phase in which the machine became a great social leveler. Gunpowder destroyed feudal military forms; through printing, books became available to everybody, rather than being only the property of the rich; the clock provided a uniform standard of time which, from then on, has relentlessly paced the life of rich and poor alike, parceling their time in ever smaller segments as the precision of the mechanism increased.

Later in this period, the invention of the steam engine further expanded our muscle and, later yet, the internal combustion engine and the electric motor made power more democratic, available to everybody. By the end of the mesobiosoma our great dream of flying was fulfilled and many serious infective diseases were conquered. We also became able to communicate instantly across a globe.

The democratization of information and personal power is of this period also, giving birth to new social forms, the state with universal suffrage, the modern corporation, the professional society. At the same time, our accrued physical power made human conflicts more devastating, and facilitated the creation of the totalitarian state.

(e) The Contemporary Biosoma (from the middle of the 20th century)

In the middle of the twentieth century, the biosoma entered into a phase, in which the dramatic expansion of the powers of machines and social organizations has not only revolutionized our lives and our station in the universe, but also placed our species in danger of extinction. Our future now ceases to be bound to the future of the Earth, but also stands in a delicate balance between triumph and disaster.

In effect, we have come full circle. The primeval biosoma made possible our survival and our emergence as a new tool-using and social species. Today, the continued development of the biosoma places us in a position analogous to when we first attempted to survive by breaking away from other species and from a habitat that had become hostile to us. As it did some six million years ago, the combination of machines and social structures as well as the growing ability to modify biology gives us, today, a chance to survive in new environments, and in large numbers. If the combination fails us, we are doomed. If it enhances us, it will bring the universe within our reach.

The contemporary biosoma has not only dramatically stepped up the extension of our skins, muscles and brain, and made it possible for us to move into space, but also has given us the ability to manipulate genes and thus intervene in the process of biological evolution. At the same time, the biosoma has become more diffused than ever. It has become truly global. In the technologically more advanced countries, every one of us has come to depend for our existence on an unprecedented array of machines and social devices. In the technologically less advanced countries, the dependence may be lower, but real enough, and the aspiration to a more developed biosoma has become irresistible.

To function in a technological society without an automobile or a telephone, without access to markets, hospitals and schools or, increasingly, to the Internet, is virtually impossible. Very few among us are now in a position to live an autonomous existence, to grow our own food, build our own shelter, to heal our illnesses. Even those who endeavor to do so depend on machines and social organization, on books, electricity, education and highways.

The era has thus arrived in which not only can we not survive without machines and social organizations, but we have become dependent on sophisticated and powerful machines, many of which depend in turn for their creation and functioning on complex social organizations. This is also the incipient era of the bio-machine, the intimate combinations of machines and biological organisms such as the heart pacemaker, the artificial kidney, or genetic engineering, which augment and replace our organs and blur the boundaries between the biological and the machine. That boundary will become even more blurred, but in a different direction, with the emergence of autonomous machines capable of adjusting their goals to the environment, of reproducing themselves and of drawing from the environment the material and energy necessary for their operation.

Conceptually, today's biosoma is the last step in the evolution of its components. A new genesis has, in effect, occurred, the genesis by living matter of a new entity, the biosoma, capable in turn of creating both new living species and machines with life-like attributes. The genesis is far from complete, but the process of trial and error that made the biosoma and its components as we know them today must be far more cautious in the future, because our risk of failure and total extinction is far greater. Our future will depend critically on our ability as individuals and as a society to think of biological organisms, machines and society as partners in our evolution. Thus, it becomes important to recall and understand the crucial steps that have made each of these entities what they are today.

CHAPTER 8. BIOLOGICAL EVOLUTION AND BIOSOMA "EVOLUTIONS"

Biological, bio-social and biosoma "evolutions" differ in terms of their time scales, of the meaning of the term evolution, of the instrumentalities of evolution and of what are the fundamental questions that confront us in each.

The time scale differences are obvious. Biological evolution started before bio-social evolution, which became possible only with the advent of social interactions among more complex biological organisms, and which preceded, in turn, bio-socio-machine developments.

Evolution is a specific biological process. Strictly speaking, one should not use the term for social entities and machines, as they develop through a different process. Biological evolution has been portrayed by a single genetic tree, even if now we see it so convoluted that it could be better described as a reticulate tree (Doolittle). But, for sure, no single tree, however complex, can portray the development of all machines and social entities. If we were to draw something resembling genetic trees for these metabiological domains, they would have a different meaning and purpose.

The study of biological evolution was started by Darwin and Wallace. Systematic study of bio-social interactions is much more recent and limited, and capable of generating much controversy, as in the socio-biological theory of genes as the determinants of social behavior (Wilson, 1975). Any consideration of the future evolution of biological organisms and of society needs to consider bio-social interactions, but cannot stop there. It must also include the interactions with the machine—the biosoma concept.

The key questions in the biological domain concern the nature, origin and evolution of life. In the bio-social context, they concern the relation of societal to biological evolution (which drives which, and how?). In the biosoma domain, the key questions have to do not only with what is, and why, and with the nature and development of the biosoma, but also with the future, with what we can build in the realm of machines and social organizations. This is so because machines, and much of society, are designed for a purpose, the purpose that eludes us in biological organisms. Hence, the questions exist of how we can influence the interactions, and of the extent to which our future will or should be shaped by individual biological drives, societal teleology, or technological determinism.

The instruments of evolution are different in the three domains, but ultimately the evolution of the biosoma is an integration of the processes that govern the evolution of its components. In biology, the instruments of evolution are, clearly, the genes, together with influences from environment, including competition from other species and organisms. In the socio-biological context, the genes, as instruments of evolution, are complemented by the collective minds, rational as well as emotional, of social groups. Societal expansion of the purely biological context and its rules is characterized by social rules, some of them implicit or innate, others explicit and by design, such as laws or constitutions. With the biosoma, enter the machine. Machines, too, are governed by rules for their design; the key agents of their evolution are the minds of the designers. Design is influenced by the demands to extend and complement human capabilities, by the availability of resources—energy, materials and information—and by the impacts that a machine may have on the rest of the biosoma and on its environment.

Key to the evolution of all entities, whether biological, bio-social or biosomic, is the acquisition of knowledge. Biologically that acquisition occurs innately, as well as through experience. In the bio-social domain, those two mechanisms are complemented by education, through the interaction with other humans. In the biosoma domain, knowledge can also be acquired from machines (that is, indirectly, from the humans who designed them) and by machines that are given the ability to acquire it autonomously.

Evolution in the biological domain occurs generally by small steps (although, as we have noted in Part I, under special conditions some of the steps can occur fairly rapidly in certain species). In the bio-social domain, there is the possibility of grand designs. Great political theories and great religious views have deeply influenced human history. However, social factors other than a grand design also have a major influence on biology, such as the selection by females of males that are powerful, not in the purely biological, but also in the social sense.

In the biosoma domain, even grander designs are possible, such as influencing biology through direct intervention on biological organisms—humans as well as other species—or the possibility of life escaping the Earth's gravity. Unfortunately, in the grand design category falls also the use of weapons of mass destruction to obliterate an adversary in a way never possible before.

Biosoma Dynamics

What happened in Europe from classical times to the Industrial Revolution provides a good example of the complex dynamics of the biosoma. In the classical period, there were great societal developments in Greece and Rome. In Greece, they were not accompanied by a corresponding dramatic development of machines. That, however, occurred in Roman times, with roads, aqueducts, thermae and some military machines (Fig. 31). Conversely, the early medieval period in Europe was in some respects one of societal regression, but of continued

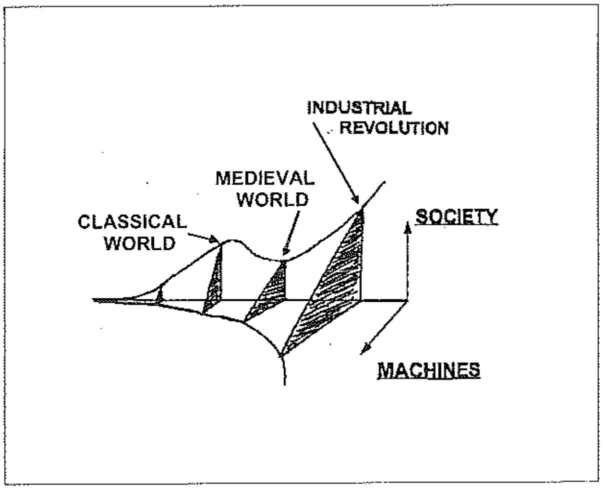

Fig. 31. Qualitative Rates of Societal and Machine Development in Western Societies

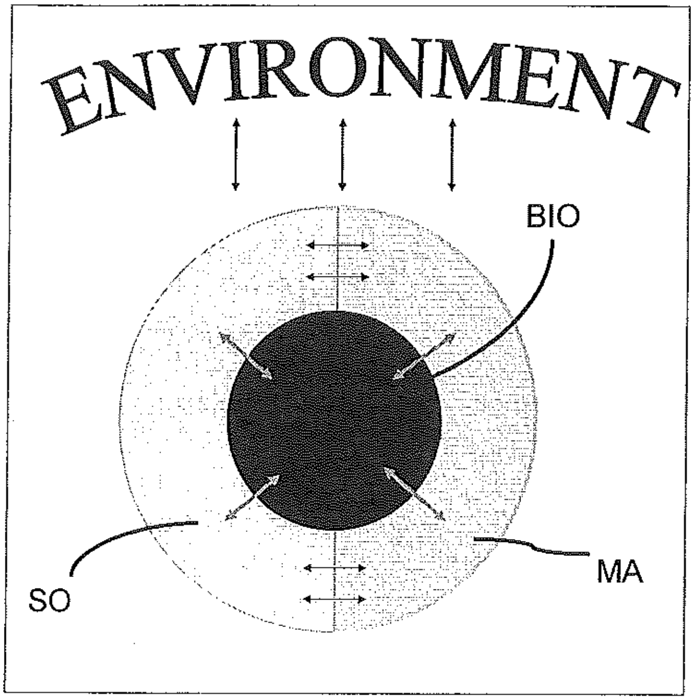

Fig. 32. A Concentric Biosoma Representation

slow advance in several kinds of machines, including the non-choking horse harness and the stirrup. In the fourteenth and fifteenth centuries, remarkable, ingenious mechanical machines were limited in their performance only by the lack of better materials and an adequate source of power. It took four hundred years from the human-powered flying machine and the vertical take-off machine conceived by Leonardo da Vinci for the first airplanes to fly, thanks to the internal combustion engine. It took even longer for the helicopters. More recently, thanks to new materials, the vision of human-powered flight became reality with the Gossamer Condor in 1977 and with the Gossamer Albatross, which crossed the English Channel in 1979. After the medieval times, the period from the Industrial Revolution to today has been one of explosive machine and societal developments. In brief, the evolution of the biosoma is characterized by bursts of creativity, in some or all of its components—biology, society, machines—rather than by continuous development. Today, we are living one of those bursts.

We could represent the biosoma as a set of two concentric circles, with the biological component at the core, surrounded by societal entities and machines, and with the whole surrounded by the environment from which it emerged in the first place (Fig. 32). The three components of the biosoma obviously have different relative importance in different human societies and condition, and in animals (Fig. 33). In primitive societies, for example, the individual is less important than the society, and machines are few and primitive. In modern, democratic, materially advanced societies the reverse is true, but machines are more closely intermeshed with society. They are ever more sophisticated and powerful, to the point that they may threaten the independence of the individual and make us fear that they have come to dominate social processes. In materially advanced totalitarian societies the individual is much less important than the state—a social organization—and its machines. Poverty manifests itself in different ways—too few machines, or too few social interactions (or, as in the case of a prisoner, too few of both) (Fig. 34).

The dynamics of the biosoma are shaped by the different characteristics of its components. Consider, for instance, response times. As already discussed, usually the social component of the biosoma tends to respond slowly to innovations in the machines component, as they often require new organizational patterns, new laws, the development of new perceptions and the evolution of new customs. In countries of the former Soviet Union, the rigid Soviet social structure and the associated frame of mind were major obstacles to the creation of a modern technological society (e.g., Bugliarello et al., 1996).

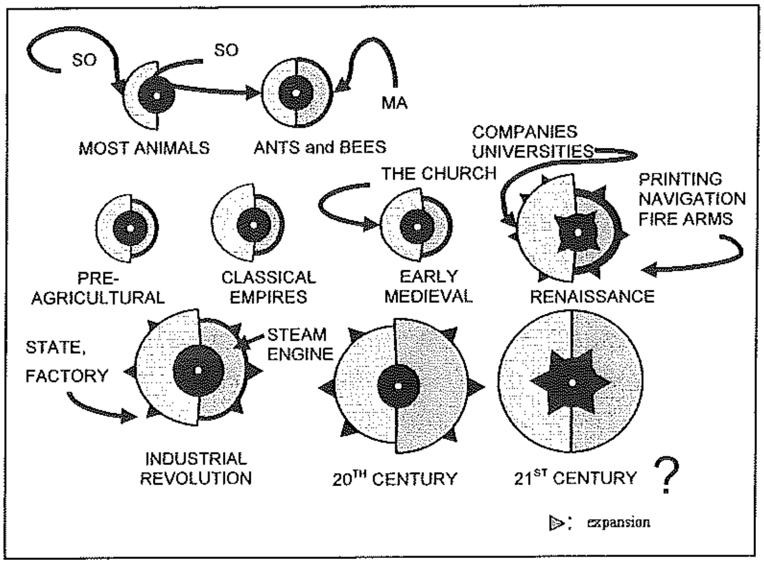

Fig. 33. The Evolution of Biosoma Components

The future of the synergy of a machine, biological and social systems cannot be completely predicted because they differ in performance. The biosoma is a coupling of the definite performance intrinsic to a specifiable machine (Chapter 2) with the non-uniform responses characteristic of both the biological and social domains. Living organisms and societal entities simply cannot respond with absolute predictability to a given input. For example, a given rate of air recycling in an office can lead to different perceptions of discomfort, since different individuals have different temperature comfort levels. This affects the well-being and productivity of the occupants. The environment with which the biosoma interacts in general not totally predictable either. This complicates the challenge of mitigating the effect of a vast array of natural phenomena, from earthquakes to droughts.

The Pervasive Biosoma

Virtually every human activity is of a biosoma nature, as it depends, directly or indirectly, on our interactions as individuals with society and machines. Agriculture, industry, commerce, education, health care, or warfare are all biosomic. So, for that matter, is an activity like literature, as it depends on machines—on a medium such as paper, on writing instruments and on libraries—and on a social milieu that encourages it. (That milieu, exemplified today by publishing houses, is made possible in turn by machines, however accessible, such as desktop printers, or expensive and complicated, such as a printing press.)

A closer look, by way of example, at agriculture, industry, health care the city and warfare should help clarify their biosoma nature.

Agriculture

The biological component of agriculture is constituted by the individual farmer as well as the plants and animals that are the object of the farmer's activities. The machines are the implements the farmer uses, from hoes to tractors, irrigation channels to weather satellites. The social component is the ensemble of organizations that make agriculture possible, from property laws to irrigation districts, from the industries that produce agricultural implements to the markets for products, and the banks that finance the farmer.

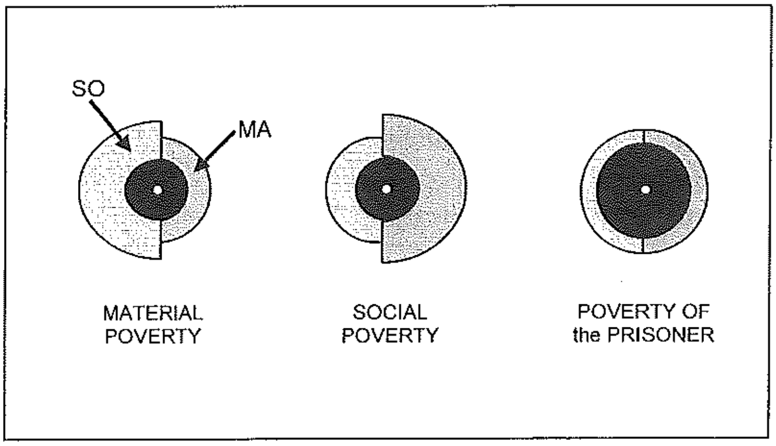

Fig. 34. Different Kinds of Poverty

Biologically, the farmer has not changed since the beginning of agriculture 10,000 years ago. Agricultural machines and social organizations, on the other hand, have changed enormously from their simple beginnings. Many plants and animals also have changed through outside interventions—breeding and selection. As a result of these changes, only a small number of individual farmers are needed today. In the U.S., less than five percent of the work force is engaged in agriculture. In some cases, farms are managed from a distance (using also advanced weather prediction techniques to decide the timing of sowing and other agricultural operations) and are heavily automated, as with irrigation on demand guided by sensors of soil moisture.

Problems arise when there are imbalances among these three components, as when the social organizations involved are too powerful, make mistakes, or oppress the individual farmer, as was the case with the Soviet collective farms and, earlier in the history of the United States, with the predatory tariffs imposed by railroads. Today, concerns are raised about the power of seed suppliers. Agricultural machines, too, may at times become so powerful or costly as to lead to changes in property ownership, such as the disappearance of small farms. Machines may also encourage excessive development of monocultures, which are more efficient for machine cultivation, but devastating ecologically and dangerous for their susceptibility to disease.

Industry

In industry, the biological component of the biosoma is the individual worker. The machines are the computers, foundries, lathes, robots, etc. The social organizations range from the factory to the market, from engineering schools to banks, from investors to patent offices, from the labor unions to transportation and distribution systems. In the biotechnology industry, the biological component also encompasses the microorganisms being produced or modified for utilitarian purposes. The microorganisms, however, unlike the human, which the biosoma is meant to enhance, are not the central element of the biosoma. They are instruments. Unfortunately, when workers are subject to the unmitigated tyranny of the assembly line, they too can become instruments. Luckily, this kind of biosomic imbalance tends to be mitigated today in the more progressive factories.

Health Care

In health care, the biological component is the patient, as well as the doctor and other professionals. (It also encompasses other biological organisms, such as antibiotics, but here too they are instruments of the human biosoma.) The machines range from the stethoscope to the surgical instrument, from the pill (an artifact) to the X-ray machine. The social organizations include hospitals, the health care professions, medical and nursing schools, the medical associations, laws, HMOs and insurance companies. In certain cultures, as in central Africa, the machines employed in health care may be poor, but certain social organizations–the family of the patient–are key elements of the therapeutic process. In our culture, other social organizations–the hospital and the insurance companies–predominate. Patients in the hospital are removed from much contact with their families, and find themselves in an environment full of medicine, but impersonal and at times frightening. The current struggle for patient rights is an attempt to redress somewhat the balance to give more voice to the individual.

The City

A rapidly increasing portion of the world population—currently about half–lives in urban areas. The city, with its inextricable combination of living organisms, and societal organizations, and the machines that support and enhance them, is more than ever a crucial biosoma phenomenon.

The city was made possible by the transformation of nomadic activities that followed the invention of agriculture some 10,000 year ago. The synergy of its three biosomic components has now become so powerful that the city is the most effective entity we have today for modifying and enhancing social and economic opportunities, for generating jobs, for reducing human fertility and for confining massive environmental change to a narrow geographical area. These characteristics account for the rapid urbanization of the world population. At the same time, however, the city is also a site of great social differences and potential social unrest, of alienation and of abject and endemic human poverty. Thus, it is a most telling example of the complexity associated with the biosoma and of its multifaceted and often unpredictable consequences. As a biosomic entity, the city is neither a machine nor a purely bio-social organism, although it is partly both (Bugliarello, 2001). And, as such, it cannot be completely specified, nor can its future evolution be completely predicted, to the chagrin of urban planners. The consequences of overlooking the biosoma nature of the city are evident all over the world, from Brasilia to the Bronx in New York City, and the barrios of Caracas, from the universality of traffic congestion to the epidemics of Calcutta.

Warfare

Warfare is a biosoma activity shaped by the interaction of individual soldiers with the social organizations in which they are incorporated—the regiment, the ship crew, the army corps—and with machines, that is, the weapons and the logistic devices, from trucks to factories to satellites, that support the military enterprise.

The biological component of military technology is not only the humans, but also the animals, typically the horse, but also the elephant and the camel, used by humans throughout history in carrying out warfare. Hosts as different as those of the Mongols, the crusaders and the conquistadores discovered the power of a strong synergy of humans, horses and weapons.

Although, for a long time, a number of societies possessed basically the same kind of weapons and of biological material—the soldiers—they often differentiated themselves by the social principles and organization of warfare. For the Greeks, warfare was of a ritual nature (Meier). From the Greek times to today, the Western way of war has been one of face-to-face warfare and often combat to death (Hanson). The battlefield has almost always involved the coordination of masses, whether they were ancient Egyptians or the Greek phalanx, the Roman legion or a modern army. For the Mongols, instead, the organization of the battlefield was extremely simple. Mobility and fighting at a distance, rather than hand-to-hand, were the key social principles of warfare, coupled with the use of terror to intimidate the adversary (Kegan, Meier).

In the history of warfare, the relative importance of the three components of the biosoma has varied. In the Roman armies, the social organization was of overwhelming importance, while the machines were relatively simple, albeit more powerful and sophisticated than those of most of their adversaries. For the Mongols, both social organization and machines were simple. In the Renaissance, the individual became much more important, the social organizations did not progress much beyond the Roman times and actually were much less sophisticated, but machines acquired a much greater importance with the development of gunpowder. In modern times, the importance of the individual soldier has been overshadowed by that of organization and machines. The hecatombs of World War I in particular showed how powerless and vulnerable human flesh was. Masses of humans simply could not prevail against well organized artillery and machine guns and could not operate without massive logistic support organizations. With nuclear weapons and precision missiles, the importance of the machine has become paramount and the need for great troop masses has diminished.

If we speculate about the future of warfare, we can surmise that the biological organism—the soldiers—will be increasingly assisted and even replaced by machines, leading to a quasi-automation of the battlefield and, with that automation, to the question of redefining what victory is. Some day in a not too distant future, it will be also possible to modify the biological component—the soldiers—after a fifty thousand-year stasis in the biological evolution of humans. The modification would occur through genetic engineering, as well as through bio-machine combinations. It may also be that these two technological trends will lead to the introduction of animals genetically engineered and combined with machines—true bio-machines—to develop a new kind of warfare. If these trends materialize, they would raise frightening questions about their consequences, starting with the ability of societies to control these new kinds of armed forces.

CHAPTER 9. BIOSOMA REPRESENTATIONS AND POSSIBILITIES

The themes of materials, energy, information and systems (Fig. 18), discussed earlier in the context of machines, extend across the entire biosoma, and offer a wealth of intriguing possibilities for the evolution of the biosoma and, hence, for our future. However, to suggest future possibilities is not to predict that they will occur. This is so because the future of the components of the biosoma is not predictable. In biology and in the social sciences, one does not have the predictive power that one has in physics (Ruse). Neither does one have that predictive power when it comes to the future of machines, as that future stems from the vagaries of the creativity of biological organisms—the humans—and from complex social processes. But, if the future of the biosoma is not predictable, it will be influenced for sure by our needs and concerns. We can, for instance, influence the support of science and decide on the extent of machine intervention on living systems, such as gene therapy or gene modification. We can decide on the biology-machine tradeoffs or synergies, such as the degree to which we delegate memorization to machines or we replace humans by machines in the exploration of space or in other difficult and dangerous tasks.

None of these decisions are easy, as there are major scientific and technical challenges and long-term implications which we may not clearly understand at the moment. For instance, we do not understand what may be the long-term biological or societal consequences of shifting to machines memory tasks once carried out by humans. Neither do we fully know where today's reliance in war on ever more advanced machines may lead us. Nuclear weapons and other weapons of mass destruction are contemplated in warfare because of their power, but also because they cost less. A force with nuclear weapons is relatively cheaper than a large conventional one. Yet, there are great potential dangers associated with the immense destructive capabilities of these military machines. The power to use them is vested in few people, and crude but effective weapons of mass destruction can be manufactured with relative ease.

The struggle of our species with infections is another example of biosoma possibilities. The body has certain mechanisms to defend itself against infection—the antibodies—which are the product of evolution. However, some infective agents can modify themselves genetically much more rapidly than the body can counteract them. Machines (drugs, etc.) can come to the assistance of the body by providing accelerated responses. The key is our ability to produce variations in those machines—in those drugs—at a faster rate than genetic modification of infective agents. We now have that possibility thanks to advanced drugs, that is, advanced machines.

In considering biosoma options, we may also wonder whether there is something akin to a law of compensatory effects. Can, for instance, machines compensate for societal inadequacies, as we seem to believe, at least in part, today? Can they compensate for failures of diplomacy or for lack of attention and affection?

To reiterate, identification of biosoma trends and possibilities does not imply a deterministic belief that they are inevitable; they can become so only if we continue to compartmentalize our knowledge and culture and if we cease to believe that humans must be at the center of the complex biology-society-machines. But the fact remains that effective bio-socio-machine systems are the key to upgrade the knowledge necessary to human survival, to provide health care support everywhere in the world, to transform the way we work and think of work and to create new communities of interest across the world as harbingers of new economic and political opportunities (Bugliarello, Spring 1996).

Biosoma Design

The biosoma concept has profound practical implication for the design of a machine or an organization, for or a modification of a living organism or for the design of an integrated bio-socio-machine complex. In the first place, what can be called biosoma design recognizes that the machine is an integral part of social organizations or processes. There is no point in designing machines without considering their bio-social environment, or in designing organizations or processes without thinking of the machines that serve them or interact with them. Thus, a business organization often must be redesigned to better accommodate a complex information system.

Machines and social organizations and processes should always be designed on the basis of the *biological* characteristics and needs of the humans with whom they interface. Designs based on stereotyped views of those characteristics or needs lead to alienation. Trivial but irritating examples are the stereotyped responses of automated telephone answering systems, or designs that assume that all humans are right-handed or male. Furthermore, a biosomic design cannot overlook considering systematically the potential impacts of a new machine or a new social organization or process on other machines (such as the impact of heavy trucks on road surfaces), or on the rest of society, or on the environment.

Typically, regardless of its context, a design proceeds through a series of steps, from the definition of the goal to be achieved, to a set of specifications, to the detailed design. In biosoma design, the first step after defining the goal is identification of what each component of the biosoma can contribute to it. Can the goal be achieved by a machine, by a social process, or by a biological organism (be it a human or other living organism)? Can a polluted body of water be cleaned by aeration or dredging, that is, by machines, or by societal regulations against the discharge of pollutants, or by biological means, such as the use of microorganisms that decompose pollutants? Or, can a birth control policy be implemented by the use of contraceptives (that is, machines), by social pressure, as has been the case in China, or by biological means, by following biological rhythms?

Biosoma design–the design of an integrated bio-socio-machine whole–differs from the traditional design of a machine or a social organization or process, as it combines, by necessity, definite and semi-definite components. The semi-definiteness of the biological organism and of the social entity with which the definite machine component interacts is taken explicitly into account. With it, one must also consider the nature of possible errors or failures, such as systemic design errors in the machine (which may be hard to detect, as in the case of software) or random errors in the biological or social component. Some failures, such as metal fatigue or disease, are intrinsic to the functioning of a biosoma component. Other failures arise from the interaction among all the components of the biosoma complex, as well as between it and the environment.

The possible sources of these failures can be identified by looking at the compatibility of the biosoma, such as materials, energy, information and systems components of each biosoma entity. For instance, the compatibility between the materials of the machine and biological materials is of paramount importance in the design of implants and bio-machines. Equally important is the compatibility between materials used in the design of machines and the role that those materials may play in society, such as their availability, or how they eventually are disposed or replaced. In terms of energy, a biosoma design would consider the availability of energy—biological and social—to build and operate the machine, and the biological, social and environmental consequences of the form of energy chosen. In terms of information, focus on compatibility leads to identification of the bottlenecks in transmission of information among the three biosoma components. These bottlenecks may not provide enough information to the machine to operate according to the wishes of the user, or may provide the users with more information than they can handle. In terms of systems, the general question is how integrated are machine, biological and social components to achieve in the best possible way a given design goal.

Sustainability and Diversity

One of the most urgent problems of today is the impact of the rapid growth of human populations on the future of humans and other species. This makes it imperative to understand the options and trade-offs that the biosoma offers us (Bugliarello, 1973). The increasingly powerful combination of humans, society and machines has made possible a human population of six billion. If that combination fails us, the consequences can be terrible, as in the case of the deadly Irish potato famine of the mid-nineteenth century. The famine was a textbook case of biosoma failure, caused by an almost exclusive reliance, for societal reasons, on the potato for human nutrition, by repeated failures of the potato crops, and by a faulty economic theory which guided the action—or inaction—of an ignorant and obdurate government. Most other tragic famines around the world are the result of systemic biosoma failures, not as much because of global limits as to what the Earth can produce (it probably could feed a population twice as large as today's), but because of local failures and misdistribution, that is, poor organization and logistics. Less dramatic, but not less remarkable, have been the nutritional changes that society has imposed on humans. Increasing urbanization forces people to have two or three concentrated feedings during the day, away from the habit of a more continuous feeding throughout the day, to which our digestive system is still physiologically geared from the times when we inhabited the forest, like our simian relatives.

In the future, a population of fifteen to twenty billion might be possible, although some of today's projections indicate a projected maximum population of less than ten billion. The question, however, even with this lower figure, is *cui bono*? To whose advantage is it to have such high population? Certainly the environment would be far more dramatically impacted than it is today, and our lives more constrained and endangered.

Most humans, like all other living organisms, want to propagate themselves. However, the machine has lessened the need for abundant progeny. Agricultural machinery has largely replaced rural labor almost everywhere and the different economic conditions in an increasingly urbanized global society, with half of the world population now living in urban areas, make children a burden rather than an asset in immediate economic terms. At the same time, however, the machine has facilitated the destruction of pristine environments and the disappearance of many species, a disastrous trend. The only mitigating factor—and it is only a slight one—is our growing ability to preserve the genetic information of those species in danger of extinction that we can identify (today, a minority of all species in existence (Wilson, 1993). This ability should not exempt us, however, from the imperative to preserve bio-diversity, because of the immense and potentially vital patrimony of genetic information embodied in the myriad of species that are disappearing. As we get to know aspects of that patrimony, we begin to understand the potential impact that it can have on health (e.g., as a source of new therapeutic drugs) and on other aspects of our lives. The loss of biodiversity is an eloquent example of the price we pay by creating and using machines indiscriminately and aggressively without fully understanding their biological and social impacts.

Ever more powerful combinations of increasingly crowded populations, profit motives and machines are reshaping our environment faster than society's ability to comprehend the consequences or its willingness to act. At the same time, however, the biosoma offers us many options or trade-offs, some of them becoming increasingly evident and being actively pursued today, but some still to be recognized and developed.

For example, *land- (or environment-) machine trade-offs* make it possible to reduce community sprawl by going vertical, by constructing high-rise buildings. We simply cannot any longer afford low-density land-gobbling habitats. *Bio-social trade-offs* lead us to explore the extent to which motivation to have progeny can be served by social mechanisms. (This puts on the table also questions of religion.) In the domain of energy, we can look at *biological* versus *environmental energy trade-offs*, using, that is, energy coming from the environment (sun, wind, tides) or geothermal energy, rather than energy from the biomass (fossil fuels, but also forests). *Energy* versus *information trade-offs* offer increasing possibilities. They range from teleconferencing and telecommunities to the achievement of fuel economy with better designs (because, as discussed earlier, design is an information-centered process), to the migration of jobs to the service sector.

The development of information-intensive agriculture reduces the expenditure of energy involved in the process, and the restructuring of the work-rewards equation can encourage people to concentrate their economic activity on high-value added, low energy-consuming services. The fact that thus far people are traveling more and consuming more energy than before is possibly a transitory phenomenon of a not yet fully developed information society. But to have an impact, these options require major societal and individual commitments.

CHAPTER 10. THE THREE KEY BIOSOMA LEVELS:

ESSENTIAL, DESIRABLE AND COUNTERPRODUCTIVE

The biological needs, the social entities and interactions and the machines necessary for our survival, our health and our human dignity define a minimum essential biosoma level that every civilized human being should possess (Fig. 35). It is a level that redefines poverty as being more than just the deprivation of food, clothing and shelter. It is a level that affects far more than the one billion people across the world that today we label as poor, if we consider, for instance, the persistence of illiteracy or the many ways in which we destroy, deliberately or not, human dignity. The fact that, on a statistical basis, we live longer, does not justify indifference to the biosomic needs of those left behind, deprived of the essential biosoma. Unfortunately, as U.N. conferences on habitats have shown, we are very far from agreeing as to what a minimum, essential biosoma level should be in different societies, and how it could be achieved.

The essential biosoma changes with age, and with the state of our health. It varies for each individual, as well as, obviously, from society to society. There are, however, certain needs, such as water, food, shelter, or affection, that are universal. There are also ever newer requirements for survival in the more complex society made possible by technological advances. In an increasingly information-based society, a new and potentially devastating kind of poverty is to be information-disenfranchised, that is, prevented from having access to the information that has become indispensable for jobs and health. It is sobering to think that in the world today well over a billion people have never used a telephone.

As human habitats extend over ever more adverse environments, the essential biosoma encompasses also the need for protection from extreme environmental conditions that are exacerbated by the artificiality of those habitats.

•Essential for — •Survival and Health •Human potential •Human dignity

•Changes with — •Age •Disease and Injury •Individuals

•Redefines Poverty (3 Components)

•Can Be Absent Even In So-called "Affluent Societies"

Some Key Needs

BIO	SO	MA
•Air	•Family	•Clothing
•Water	•Social capital	•Housing
•Food	•Schooling	•Temperature Control
•Light	•Doctors	•Sensory Aids
•Temperature	•Jobs	Glasses
•Humidity		Hearing Aids
•Other Bios		•Medicine
Plants		•Telecommunications
Pets		•Transportation

Fig. 35. The Essential Biosoma

Consider, for instance, the recurrent heat wave fatalities in cities. The several hundred in Chicago in the summer of 1995 shocked the nation. They could have been avoided if the victims had not been living in the stifling, airless cubicles of "projects," without any cooling devices, at times even without running water, with doors and windows closed because of fear of crime. Unfortunately, this kind of heat-related deaths continue to occur.

The essential biosoma redefines poverty in a more comprehensive way than we are accustomed to, as a deficiency or lack of any one of the three biosoma components–not only of food and other tangible goods. The daily essential biological requirements include, of course, 17 cubic meters of air, 1.8 liters of water, and a minimum of 1800 calories from food. Biologically, we also need light, and a survivable temperature in our environment, since, being basically liquid organisms, we can survive, unaided by clothing and shelter, only within a narrow temperature range between freezing and boiling. The social component of the essential biosoma includes family, health care, jobs and other aspects of social "capital" and the machine component includes clothing, housing, transportation and, today, telecommunications. Deficiencies in the essential biosoma are much too common everywhere, unfortunately. They range from poor air circulation and water quality, insufficient protection against heat and cold, and inadequate workplace illumination, to weak families, inadequate access to health care, job insecurity, substandard or no housing and limited or no access to transportation.

Beyond the essential biosoma, we could identify desirable biosoma levels as those characterized by a balance among biological, social and machine components—a balance that is sustainable indefinitely without destroying the environment, and that enhances the human condition and the human reach (Fig. 36). We need to remind ourselves, however, that environmental injuries and environmental deterioration are not totally a modern phenomenon. Some six thousand years ago, the Sumers over-irrigated their land in the Euphrates valley, creating salt pans and polluting their own canals. Neither are environmental changes created only by humans, as shown by the impacts of asteroids that we believe caused the disappearance of dinosaurs or by the recurring cycles of warm and cold periods in the Earth's history.

- ESSENTIAL
- DESIRABLE
  - Balanced
  - Sustainable
  - Enhancing
- COUNTERPRODUCTIVE

Fig. 36. The Three Key Biosoma Levels

Inability to avoid imbalances among the three biosoma components leads to counter-productive biosoma levels. For instance, machines can unduly influence the development of society and consume too much of our resources, let alone physically destroy us through war and terrorism. Or, a social component may totally overwhelm the individual, as in societies in which the individual has few or no rights. An assessment of our own society today may indeed lead us to conclude that the state of our biosoma is already counterproductive. The machines that were intended to help us develop an ever better life force us to spend hours in congested traffic and have led to a deterioration of person-to-person interactions, replacing them with person-to-machine ones. The question is whether our present condition is transitory and will eventually lead to a more balanced and desirable biosoma, or whether these trends will be exacerbated.

Biosoma Pathologies

Pathological dysfunctions are often the key to understanding a system (Lorenz). The pathologies of the complex system that the biosoma is can help us to better understand its nature and characteristics (Fig. 37). Some pathologies are obvious, even if their diagnosis does not lead necessarily to cure. For instance, sickness is a pathology of the biological component, lack of discipline a pathology of the social component, and technical failures are pathologies of the machine component.

But there are also pathologies of the biosoma as a whole, often less obvious but more insidious. They range from imbalances among the components of the biosoma (e.g., excessive mechanization of the biological component, or stereotyped environments that leave us little freedom, *de facto* prisons) to systemic failures associated with poor bio-machine or bio-social communication, or poor social-machine interfaces. We encounter every day these disconnects among the three components of the biosoma. The list is long. It includes human errors in driving a car, piloting an airplane or operating other kinds of machines, with potentially disastrous consequences, like Chernobyl; social organizations that rely on machines of inadequate capacity, such as toll gates, or too few toilets in a crowded theater at intermissions; individuals that depend on an inflexible bureaucracy; machines depending for their continuous operation on a maintenance organization that responds too slowly; cars that allow for speeds that are too fast for human reaction times; abundance in one place and poverty in another. The challenge, once we succeed in diagnosing the causes of these pathologies, is to find appropriate remedies. This is difficult but not impossible, unless we acquiesce to a kind of biosoma fatalism.

•PATHOLOGIES OF THE COMPONENTS

BIO •SICKNESS
•AGGRESSION

SO •DICTATORSHIPS
•LACK OF COMPASSION
•LACK OF DISCIPLINE

MA •FAILURES
OF COMPONENTS
OF SYSTEM

•PATHOLOGIES OF THE WHOLE

- •IMBALANCES AMONG COMPONENTS
  - •OPPRESSION & NEGLECT OF *BIO*
  - •EXCESSIVE *MA*
  - •TOO LITTLE *MA*
  - •OVERBEARING *SO*
  - •TOO LITTLE *SO*
  - •ALIENATION
  - •*DE FACTO* PRISONS
  - •DRUGS (BIO-MA PATHOLOGY)
- •SYSTEMIC FAILURES

POOR: •BIO-MACHINE COMMUNICATION
•BIO-SOCIAL COMMUNICATION
•SOCIO-MACHINE COMMUNICATION

Fig. 37. Examples of Biosoma Pathologies

CHAPTER 11. FUNDAMENTAL BIOSOMA QUESTIONS

How far can we extend our biological capabilities extracorporeally, through machines and societies? We could say, "as far as we can, compatibly within the constraints imposed by the very nature of the components of the biosoma—the limits of biology, of engineering and of society." That answer, however, subsumes two fundamental questions: What is the essence of being human, and what do we want to be? These questions have had to be addressed repeatedly in the evolution of humankind. When we emerged from the trees and decided to trust our future to an ability to survive in the open, we made a decision based on instinct and necessity. We do not know how many other times afterwards we made other momentous decisions in our evolution to modern humans. We made them out of instinct and necessity. With the ancient Greeks, the question of what is the essence of being human was explicitly addressed in rational terms. Starting with them, humans evolved powerful mechanisms to reason about these questions—intellectual mechanisms that ultimately made modern science and modern engineering possible (Knox).

With today's advances in engineering and science, with the possibilities created by bio-machines and genetic engineering, the questions of what is the essence of being human and of what we want to be—not only morally and socially, but now also biologically—are, again, squarely on the table and have acquired an unprecedented urgency. Biology, to use Knox's happy phrase, "does not need to set any longer our station in life." We have the opportunity to change, for utilitarian purposes, but also because of our innate urge to seek and create. The utilitarian purpose, however, cannot become so pervasive as to lead to a society driven only by the obsession to produce and consume more, regardless of need or of the dangers to our own survival. Similarly, the creative urge should not put our species and the environment at risk, as it has done with nuclear weapons and as it may do with unwise genetic engineering or bio-machine developments. In either case, the greatest danger arises if we acquiesce to technological determinism, to the "if it can be done, it will be done." Neither can we, however, turn the clock back and stop creating and producing, lest we become powerless to survive in a nature that we are now irrevocably changing, but that continues to be majestically neutral as to the fate of our species.

Ultimately, to what purpose, and to what extent and under what conditions should biological organisms be modified and societal and machine components altered? How do we prepare our global society for the creation of new niches and new chapters in the trajectory of our species that the vertiginously rapid development of ever new machines and of our knowledge is opening to us? And, looking far ahead, is it possible for our species, by a wise evolution of the biosoma, to stave off the disappearance that has been the fate of most other species? To what extent are we willing to surrender part of that control to a biosomic global intelligence (a "hyperintelligence") integrating human, social and machine intelligence (Bugliarello, 1990)?

The Question of Checks and Balances and Control

To deal with these issues we need a system of biosoma checks and balances. The problem is that even if there were such a system within each component of the biosoma, the biosoma as a whole does not have it. The most stable and successful internal checks and balances are in the biological component. They have evolved over billions of years and manifest themselves, for instance, in homeostasis, that is, the balance within the organism, and in ecological equilibria, the balance among competing species. It is not, however, a system that guarantees biologically the survival of our species, even if it operates very effectively internally to our organisms. Hence the importance for our survival of a balanced set of metabiological extensions. The checks and balances of a social system are less stable, although historically there have been some examples of long-lasting social systems. Ancient Egypt survived, as a theocratic regime, some three thousand years. The republic of Venice, the longest lasting electoral government on record thus far (although not democratic, as not everyone could vote) was obsessed by the question of checks and balances. It survived for a thousand years. The university, with its own peculiar system of checks and balances, is now a thousand years old as an institution. Today, checks and balances occur in many other social systems in the form, for instance, of regulatory agencies, boards of directors, or of required balances of income and expenditures.

The checks and balances of machines, besides those inherent in the laws of physics or chemistry, or in design logic, are imposed from the outside and are the weakest. In the simplest case, they take the form of feedback systems that keep some operating parameters within limits. Unlike biological and social organisms, however, in a machine those balance mechanisms are designed into it from the outside, rather than being an intrinsic characteristic.

In the measure that biological and social systems depend on machines, their systems of checks and balances can become weakened and both individuals and organizations—ultimately the entire species—can be placed at risk. Powerful machines can confer an enormous power to individuals or societies. Without adequate checks on its use that power can be destabilizing and destructive.

The enormous multiplier of physical power made possible by machines in terms of energy, information, materials and speed has consequences that range from information overloads, to high levels of noise, excessive consumption with accompanying environmental damage, and disproportionate use of force. A telling example of the impact of speed is the elimination of quarantine. The old concept of keeping travelers segregated for a period of time to assess the possible existence of infectious disease is not practical any more in an age of global air travel. On the other hand, the very speed of machines can accelerate the discovery and production of protective measures through vaccines or the diffusion of information.

A powerful source of imbalances is the rapidity with which we can produce machines in very large numbers, before deleterious effects are noticed and corrected. We may recognize too late the side effects of a particular drug or medical procedure, or the environmental impacts of an industry or a device.

The difficulties in controlling these imbalances are at the base of our doubts about a future of sustainable development for our species. For the sake of our future, individually and collectively, the control of the biosoma cannot reside exclusively in the dictates of individual genes or in those of society. The need is for a balanced integration of social and biological drives, an integration that cannot be achieved without considering the machine. The human component, in virtue of its semi-definable nature, can behave unpredictably, and is powerfully affected by psychological factors. Society also, as another semi-definite entity, can be highly volatile and idiosyncratic, as shown by rapid swings in popular mood, or the enormous emotion at the death of celebrities. The machine, in contrast to humans and society, is reliable and unaffected by psychological factors.

The crux of the matter is how to find and maintain an enlightened balance among the three components of the biosoma, with their different characteristics, potentials and pathologies. This raises difficult questions that we do not yet know how to answer. We know, however, that if change occurs in the biosoma, it should occur not because of inadvertence, but because we understand it, see its benefits and want it to happen.

On a more immediate plane, can an unsustainable consumer society be transformed by taking advantage of the options the biosoma offers? How can we cope with the impact of machines on traditional forms of employment and with the weakening of our identification with work as a mark of our worth? Can a better understanding of the biosoma help us to reduce the very dangers and lethality of war that the biosoma has enhanced in the first place? And how do we assure every human being of that essential biosoma which is the minimum level compatible with human health and dignity? What are the advantages of the ever longer life expectancy that today's biosoma offers us? With the muscle of society being provided more and more by machines, information and knowledge become the key theme of society. But will the greater knowledge intrinsic in an older population be counterbalanced by those rigidities in thinking and that unwillingness to try new approaches that often come with old age? Also, is it possible and desirable to control aggressive drives that are a throw-back to earlier times? Can we do so without weakening the creativity of our species, thereby accelerating its demise, now that we are so far out on an evolutionary limb that it can only be sustained by new biosoma inventions? We can hope to find answers only if we stop our compartmentalized way of thinking, learning and doing.

The Question of Integration

Biological evolution has been a continuing search for niches. Machines and societies have expanded immensely the niches available to human beings. When we think of the future of our species, we need to remind ourselves that biologically the decks are stacked against us just as they are against any other species. If we are not to follow the eighty-three percent of the species that have vanished since the beginning of life on Earth—and usually these are the larger species—we need to better integrate our knowledge of nature and of how we modify it, with our ability to decide whether, and to what extent, we should modify it. We need, in short, to better integrate the three questions first raised by Kant: the *whys?* the *how?* and the *should we?*

The coupling of this integration with that of the three great biosoma domains of biological organisms, of machines—that is, the human-made—and of society (Fig. 38) can give us the instrument for rejecting both unfounded hopes and hubris about our future. The unfounded hopes are just that. They are the hopes that we shall survive no matter what and hence we should accept things as they are, without undue worries about ozone holes or disruption in habitats. But it is clear that this can give us very little confidence about the future. It is hubris to think that we know best, that, because we are human, and with our brain larger and more developed than that of other species, we will always succeed in overcoming obstacles. The fallacy in this argument is that the history of our species is very limited, less than six million years. We just do not know enough about the vicissitudes that made us what we are. Neither do we know what are the consequences of our actions today or, for that matter, of natural changes in the environment, such as the long cycles of warm and cold temperatures that gave us the last Ice Age and the warmer stretch of the last 12,000 years.

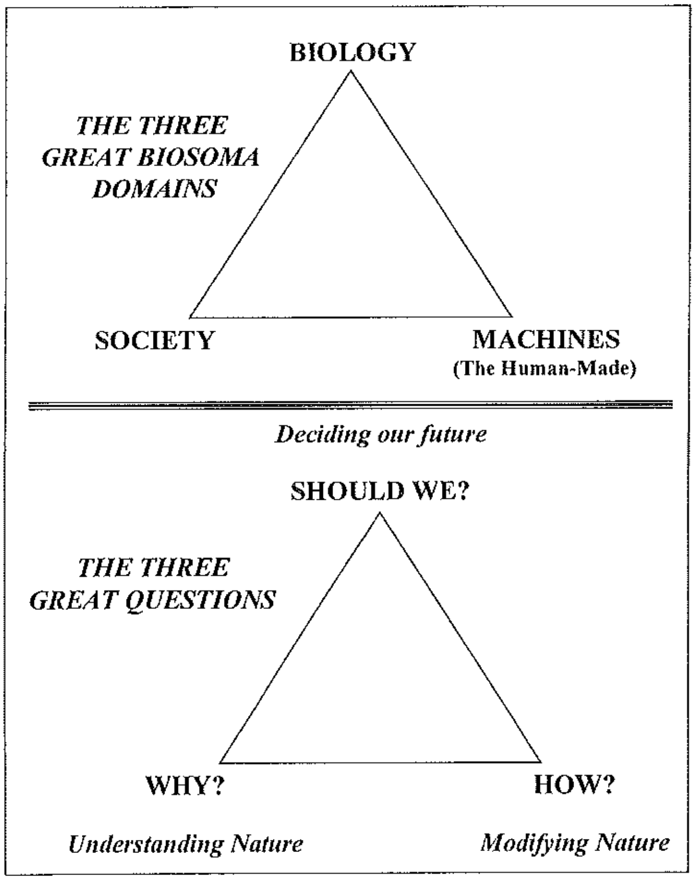

Fig. 38. Integrations of Knowledge

Thus, we cannot accept passively what is unknown or unintended in our future. We need instead to prepare ourselves for the future by integrating all our knowledge and our ability to decide and act intelligently. This requires, to begin with a deep dialogue among ethicists, scientists and those who modify nature by creating machines or intervening on biological organisms, from medicine to agriculture.

The need for integration has been felt for a long time in human history (Fig. 39). Already, Aristotle, in the work later labeled "metaphysics," looked beyond physics to aspects of what we would call today humanities-ethics studies. Thomas Aquinas endeavored to bring together science and religion. The humanists of the Renaissance actually succeeded in integrating in their studies both science and the humanities, as well as biology and machines. Leonardo, with his great genius, brought together science and machines, as well as art (that is, as discussed earlier, another kind of modification of nature), as well as biology and machines. In a different vein, in the fourteenth century, the Arab scholar Ibn Khaldun, in his *Introduction To History*, endeavored to provide a comprehensive view of the human condition that touched upon biology, society and the environment, and included the crafts, but, again, did not focus on the nature, role and impact of machines (Khaldun). Today, the still embryonic Science, Technology and Society movement looks at the integration of these three domains; bioengineering endeavors to bring together biology and machines and socio-biology focuses on some

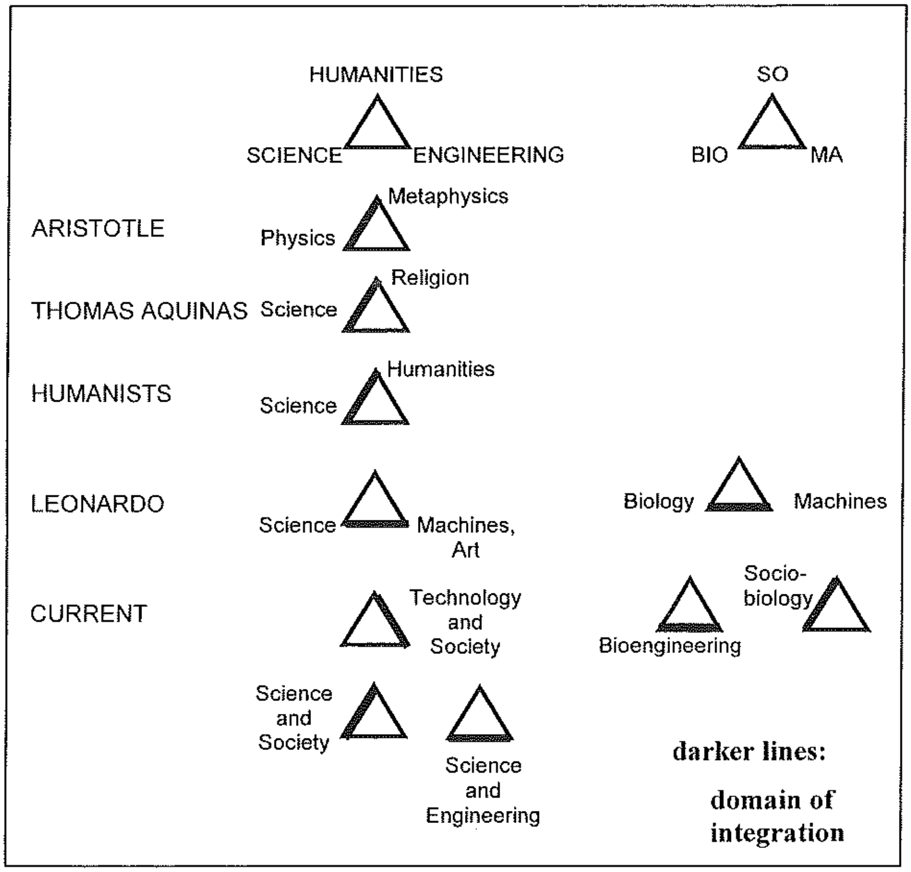

Fig. 39. The Quest For Integration—Historical Examples

aspects of the relation of biology and society.

Recently, E.O. Wilson has stressed the importance of the confluence of environmental policy, ethics, social sciences and biology, that is, the integration of biology and a set of societal concerns ranging from social science to environmental policy to ethics (Wilson, 1998). That is the integration of the *whys* of nature and the *should we*? However, it leaves out direct consideration of machines.

As the humanist Knox suggests, "The second choral ode of Sophocles' *Antigone* begins with the famous celebration of the *technai*, the arts and sciences, which have brought man, step by step, from helplessness to the mastering of his environment and his crowning achievement, the creation of the State. *Techne*, the song seems to suggest, is the instruments by which man can make himself immune to the vagaries of destiny..." (Knox). In the speeches of Hemon and Tiresias a biosomic ideal *ante literam* emerges, "to be flexibly responsive to the world, rather than rigid...a way of living in the world that allows an acceptable amount of safety and stability while still permitting a recognition of the richness of value that is in the world" (ibid.). The integration of the biosoma can make this happen. If successful, it can set us on the path to a future of unlimited duration and unlimited possibilities, as we free ourselves, now midway in the life trajectory of the Earth, from the strict constraints of a purely biological evolution and from destructive biosoma imbalances.

Religion

Religion and religious organizations are bio-social entities that strengthen social bonds and help humans confront the great questions and vicissitudes of life. To the extent that they use machines—books, churches, statues, television, or pyramids—they are also biosomic. Printed books had a crucial influence on the success of the Reformation, the Bible is a perennial best seller, and the temple and the cathedral are great reinforcers of religious feelings.

However, the biosoma is also a source of stress for religion. The development of artifacts to operate on the body and in the body, from contraceptives to the creation of true bio-machine syntheses, can impinge in a seemingly irreconcilable way with the dogmas of some religions. It is a conflict quite different from the historic one between the Catholic Church and Galileo as to whether the cosmos was geo-centric, or from that between religious creationists and biologists, as to whether we were created whole or we evolved from other species. In both of these cases what was at issue was scientific proof, which, when irrefutably demonstrated, could force religion to reconsider and retreat. In the case of the intervention by machines or through machines on humans and other living systems and of the possible synthesis of biology and machines, the issue is not any more one of the truth of something which can be verified, but rather one of whether those interventions should occur and, if so, to what extent. An example is Mohammed's tenet that God's creation—especially people and animals—must not be duplicated by humans. That tenet led Islamic art to concentrate only on Arabesques—on geometric and floral motifs. Without even addressing the (secondary) question of why plants as another of God's creations could, however, be allowed to be duplicated in images, the tenet raises enormous questions as to what duplication by humans means. They range from that of images, now made near-ubiquitous by photography, to the much more profound questions raised by cloning, artificial organs (created to reproduce as much as possible the function of biological ones), and genetic engineering, whereby humans are now modifying God's creation.

Thus, the human interaction with machines confronts many religions with questions they did not originally contemplate, and that are even more fundamental than contraception or artificial insemination. For instance, does a machine with some degree of consciousness possess a moral dimension? Is a machine with a biological component—a bio-machine—entitled to the traditional respect that we give to life? (How far we are from this concept is evident if we think, even without considering machines, of how unceremoniously we slaughter animals biologically very close to us, animals that have in common with us most of their genes.) Where would we draw the boundary between machine and biological organism? Would a religion differentiate among a human with a pacemaker, a human with a hippocampal stimulator and a human altered by genetic engineering? If we alter genetically our offspring through the use of machines, are they still our offspring, and deserving of our religious respect? Is it sinful hubris to modify life and create human-machine combinations? Furthermore, if the machine is a human offspring (as, indeed, it is—the creation of our minds and labors, if not directly of our genes) should it also be viewed by religion as a creature of God, just like our biological offspring? St. Francis looked at animals as our brethren. Should religion make a similar leap to machines as our offspring? If so, do we owe machines respect, particularly if they are endowed with consciousness and self-replicating capabilities? (This, of course, would reduce the cavalier and environmentally damaging attitude we manifest when we discard machines, even the most complex ones.)

CHAPTER 12. CONCLUSIONS

The goal of these reflections has been to underscore the need for a new vision to address the explosive growth of machines and what it means to us as individuals and as a society. Two concepts are key to that vision:

The first is that the machine is a metabiological entity. It is a continuation of biology by other means, that complements and enhances biological organisms and society. The evolution of machines tends to bring machines and biological organisms closer to each other. It increasingly introduces machines into biological organisms and biological concepts into the design of machines. Thus, the biological organism gradually acquires characteristics of an artifact and the machine those of a biological organism. The creation of advanced bio-machines could virtually dissolve the boundaries between the two, but already, today, the blurring of that boundary is revolutionizing medicine, industry and agriculture.

In this context it is useful to distinguish between definite and indefinite performance entities. The performance of functional machines (or simply "machines" in a narrower sense) is definite; that of artistic machines (or, *tout bref,* art) is indefinite; and that of biological organisms and society is semi-definite, as it can be specified or predicted only in part. Neither totally predictable would be the performance of machines that may soon become endowed with some elements of consciousness and hence some freedom of choice. The intriguing dilemma for us will be when to accept that freedom with its advantages and when and how to override it if it exceeds certain limits.

The second key concept is that biological organisms, society and machines have come to form an indissoluble entity—the biosoma—that shapes our lives, has placed our species on an irreversible path and has given us a new perception of the human potential (Fig. 40). As a dramatic departure from purely biological evolution, the concept of the biosoma has value for our species only if it reduces our biological risks, making possible different survival strategies than those of other living species. The survival and evolution of our species depends on our remaining in control

- •Indissoluble synthesis of biology, society & machines
  - •The Essential Biosoma
- •Humans can modify themselves
  - •Meta-Darwinian & Freudian Revolutions
  - •Bio-Machines
- •Humans can modify other living organisms
- •Humans can modify the environment
- •Humans can escape Earth's gravity
  - •Meta-Newtonian Revolution
- •Hyperintelligence
  - •Global biosomic intelligence

Fig. 40. The Biosoma and the New Perception of Human Potentials

•EGYPT	CENTRALITY OF SO (Pharaonic Theocracy)
•GREECE	CENTRALITY OF BIO (Man measure of all things) A NEW SO (The *Polis*) BIO-SO BALANCE (5^{th} century Athens)
•ROME	CENTRALITY OF THE STATE (SO)
•THE GREAT RELIGIONS	CENTRALITY OF GOD (Religious SO)
•MEDIEVAL EUROPE	CENTRALITY OF EARTH
•RENAISSANCE	•CENTRALITY OF MAN and REASON (Humanists, Leonardo) •CENTRALITY OF SUN (Kepler, Galileo)
•18th CENTURY to Mid 20th CENTURY	• REAPPRAISAL OF BIO • DEMOLITION OF SEPARATEDNESS of HUMANS and ANIMALS (Darwin, Haeckel) • BELIEF IN PROGRESS (Encyclopédie) • DEMOLITION OF BELIEF IN PURE RATIONALITY (Freud) Nationalism Totalitarianism → World War I World War II
•POST MODERN	•THE "TWO CULTURES" •CYNICISM ABOUT PROGRESS •CONCERN ABOUT ENVIRONMENT •FEAR OF TECHNOLOGICAL DETERMINISM •DECONSTRUCTIONISM

Fig. 41. The Biosoma and the Evolution of Human Thought

of the biosoma rather than indulging in a *laissez-faire* attitude toward its future development. To achieve that control we need to rethink our education at all levels, an education that remains, today, dangerously compartmentalized. The concept of a human-centric integration of our biology with society *and machines* is a new step in the long evolutionary chain of human thought, from the human-centric world view of the ancient Greeks, to the state-centric one of the Romans, the god-centric universality of major religions, the sense of duty of the Confucians, the conception of liberty of the Magna Carta, to the belief in physical and social progress of the nineteenth century, and its sober reappraisal in the twentieth century (Fig. 41).

If we succeed in integrating harmoniously the three components of the biosoma we can hope to defy the destiny that has brought to extinction so many species in the history of the Earth. We can hope, that is, to escape the limitations of our biology, without being imprisoned in the strictures of technological determinism or of an anachronistic denial of the potential of our machines.

Today, we are still at an early stage of the development of the biosoma, a stage that has occurred largely by happenstance and as yet far from well understood. We can now aspire to progress to a more enlightened stage, with a clearer sense of new possibilities, new trade-offs, such as the ability to conduct war by proxy through machines, and new syntheses, from bio-machines to combinations merging the functionality of the engineered machine with the sensitivities engendered by art. Advanced socio-machine syntheses can bring together the power, speed, economy, reliability and durability (but also rigidity and insensitivity) of the machine, and the purpose, intelligence, flexibility, and humanity of the societal component. The recurring questions, as we examine these possibilities, are not only how far *can we go*, but how far *should we go*, what are we and what do we want to be. These questions have evolved throughout human history. The question of what we are was perhaps first asked by Protagoras of Abdera in the early 440s BC, who concluded that, as it was impossible to know anything about the gods, man was the measure of all things (Meier). In mid fifth century Athens, as Meier puts it, there arose a sense of the ability of humans to solve the most varied problems through craft and knowledge. However, the Greeks of that golden period for human intellect did not recognize the possibility or desirability of transforming one's nature. Everything focused on the present. In the Middle Ages, the gaze of man in the Western world became affixed to God, as the central reality and aspiration (Taylor). The Renaissance returned to the centrality of man posed by the Greeks, but, again, the question of the future was addressed only much later. De Tocqueville asking "where are we headed?" said that no one could answer because we have no base for comparisons (De Tocqueville). The sense of progress and optimism of the early twentieth century was shattered by the hecatombes of two world wars and the century's devastating totalitarianisms. It gave way, after the second World War, to the wave of post-modernism, which pessimistically saw our life dominated by technological determinism (Randall).

With the biosoma, we see ourselves at the center of an indissoluble whole that joins us to the machines and society we have created, and we place our hopes for the future in our ability to control and shape that whole wisely. Biological evolution has been occurring over billions of years. The vertiginous speed with which we are creating ever more pervasive machines is making the biosoma develop so rapidly that it cannot benefit from the slow crucible of an evolutionary process. This puts us at an unprecedented risk. At this moment we stand poised, as never before in the trajectory of our species, between the possibility of ever greater triumphs and ever greater disasters. It is a colossal gamble. Our future—what we will be or can aspire to be—will depend on our will to turn the gamble into opportunity by transforming the dynamics of the biosoma from happenstance to enlightened guidance. But gamble or controlled development, the sobering fact is that we cannot retrace our steps—we cannot pull back.

The reality of a burgeoning biosoma, in giving humankind an ever greater power confers upon us new rights but also new responsibilities. It demands new rules to preserve life and ensure the future of our species. The age-old questions about the relationship of individual to society that were at the core of Socrates' trial and of that of

Thomas More are now flanked by those of the relationships of individual to machines, and society to machines. These questions cannot, any longer, be resolved one by one, but only in an integrated fashion within the framework of the biosoma. The Earth's inevitable destruction some five billion years from now is so far away in time, that the history of our species and of other species makes it far more likely that we will disappear long before that because of other natural events or of fratricide. It would be immense hubris to believe that we could escape that fate, were it not for the fact that through the biosoma, for the first time in the history of the Earth, a living organism has the potential of shaping its future rather than just accepting what evolution and the environment dish out. However, the biosoma's potential can turn into ashes if we do not respect certain caveats:

In the first place, *the individual must be protected against biosoma imbalances* that can overwhelm the individual with the ever more powerful collective machines that only society, rather than the individual, can now build and operate.

Secondly, *no change in any of the three elements of the biosoma should occur without first considering its impact on the rest of the biosoma and on the environment.* Today, much too lightly or inadvertently, we misuse humans, or destroy the environment by engaging in a senseless consumerism. No machine should be introduced without our understanding its impacts and no machine should replace a human being without thinking of the social implications of that action. By the same token, no human being should, without a compelling reason, be asked or forced to carry out dangerous or benumbing tasks that could be performed by a machine.

In the third place, *any new development of machines or social organizations or practices needs to consider the possible biosomic trade-offs to achieve the same goals.* The potential trade-offs among biological, social and machine approaches are myriad, from contraception to education. Some of these trade-offs become imperative for the survival of the species, as in new ways to wage war.

Fourthly, *every human being should be assured of the essential biosoma*, and not be deprived of it under any circumstances, except in the preservation of the essential biosoma of other human beings. It does not weaken a human and humane society to make more bearable the life of its most unfortunate members. An intelligent combination of individuals, society and machines offers, for the first time, the human race the possibility of providing every human being with that essential biosoma.

Lastly, *the biosoma must, by necessity, be human-centric.* It must first and foremost assure the survival and extend the reach of our species. However, the human-centric biosoma, by conferring enormous powers to humans over other living organisms and their societies, and over the inanimate environment, demands that we humans, in our own interest, use those powers responsibly.

Appendix I

Further Examples of Taxonomic Trees for Machines

A further example of many kinds of machines that extend our biological muscles is the very large category of machines powered or activated by fluids, from the sail to the water wheel, the Dutch windmill, the hydraulic turbine, the steam turbine, the gas turbine, all the way to the liquid rocket and nuclear explosives. The gas turbine was made possible by the extraction of oil. In turn, oil extraction was made possible by the evolution of wells, from dug to hand-drilled to machine-drilled, and by steam or other power sources.

The development of fluid-powered machines such as turbines can be mapped as a tree also in terms of the kind of fluid they use. Thus, wind-machines range from sails (and there has been a great deal of evolution within the sail itself) to windmills, to the Flettner rotors, with their aerodynamic lift. Machines using water range from water wheels, in their large variety, to hydraulic turbines. Steam turbines belong to a different tree, that of steam machines, made possible by advances in thermodynamics and fluid mechanics with, at their origin, steam pistons. (We should not overlook for historical completeness the rotating steam engine of Hero of Alexandria two thousand years ago.) That tree of machine development leads ultimately to gas turbines, which, in addition to thermodynamics, and fluid mechanics, and to what was learned with water turbines, depend also on the technology of oil and gas extraction. (We may note that hydraulic and aerodynamic machines, from water wheels to sails, to windmills and hydraulic turbines are passive machines, but gas turbines are not.)

Advances in fluid-powered machines also reflect progress in materials, from the skins that may have been used originally in sails, to the high-performance metals that have made gas turbines possible. Another connected taxonomic diagram could represent the progression in the controls of machines, from hand levers to the simple Watt regulators all the way to today's computer controls with fuzzy logic.

Among examples of other kinds of machines we might consider are those that, in effect, extend our legs. They range from bridges to cars to spaceships. A taxonomic diagram for bridges would portray their evolution from trees placed across a stream, to wooden bridges, to stone and metal bridges. Possibly even before wooden bridges, the diagram would branch out with suspended fiber bridges, all the way to the Brooklyn Bridge and the modern suspended bridges. At every step, the progress has been made possible by collateral advances, such as underwater construction techniques for the piers or the ability to manufacture wires of sufficient tensile strength that was key to the design of the Brooklyn Bridge.

Continuing with these examples, still other kinds of machines can be viewed as extenders of our skin. They range from clothing to housing to the controlled environment of an air-conditioned room, a submarine or a spaceship.

Appendix II

A Note on Bio-machines

In terms of bio-machine goals, today's prostheses, which are used to replace or repair a diseased organ or function, are in effect the forerunners of what can become a much more ambitious process to meld machines and biological organisms. If until today the major focus has been on the replacement of hips and hearts, on heart pacemakers, on artificial skin and on medicinal drugs, we are now beginning to create chips that can recreate some brain or nervous system functions.

The challenges in the design of bio-machines include not only a full understanding of the biological functions with which the machine interacts, but also compatibility of materials and the integration of the biological element and the machine through reciprocal conveyance of energy and information. Here again, the ability to self-repair, as well as the ability for the bio-machine complex to grow, that is, for the machine component to follow and match the growth of the biological component, are major design frontiers. The energy for the functioning and growth of the machine component could come from either the biological or the machine component, or from their interaction.

Notes

1 When not confusing, I shall use henceforth the term biology both to indicate the discipline and as a generic term for the laws or phenomena relating to biological organisms, or, *tout bref*, for the biological world.

2 Bailey's English dictionary (Bailey, 1730)—the forerunner of Johnson's famous dictionary—defines:

machine as an engine composed of several parts set together by the art of mechanisms, as springs, wheels, etc., for raising or stopping the motion of bodies, used in raising water, in architecture, in military and many other affairs, motion of bodies, mechanisms and parts;

machinist, as an inventor or manager of engines; and

engine, as any mechanic instrument to produce any considerable effect which cannot be so easily and expeditiously performed by the bare use of man's hands, as raising heavy weights, water, quenching fires;

engineer as "a person skilled in the contrivance, building and repairing of forts, etc., also in the method of attacking and defending all sorts of fortified places."

Johnson, in his dictionary (Johnson, 1755) defines:

machine as 1) any complicated piece of workmanship; 2) an engine; 3) supernatural agency in poems;

machinery as 1) engineering; complicated workmanship; self-moved engine; 2) that part which the deities, angels or demons, act in a poem;

machinist as a constructor of machines;

engine as 1) any mechanical complication, in which various movements and parts concur to one effect; 2) a military machine; 3) any instrument [thereby recognizing that an instrument is a machine]; 4) any instrument to throw water upon burning houses; 5) any means used to bring to pass or to affect, usually in an ill sense (the Devil with all his engines); 6) an agent for another;

engineer as one who manages engines; one who directs the artillery of an army; and

engineering (from engine) as 1) the act of making artillery; 2) engines of war; artillery.

Webster On-line Dictionary (Merriam-Webster, 2002) defines machine as **1 a** *archaic* : a constructed thing whether material or immaterial **b : conveyance, vehicle**; *especially* : **automobile c** *archaic* : a military engine **d** : any of various apparatuses formerly used to produce stage effects **e** (1) : an assemblage of parts that transmit forces, motion and energy one to another in a predetermined manner (2) : an instrument (as a lever) designed to transmit or modify the application of power, force, or motion **f** : a mechanically, electrically, or electronically operated device for performing a task <a calculating *machine*> <a card-sorting *machine*> **g** : a coin-operated device <a cigarette *machine*> **2 a** : a living organism or one of its functional systems **b** : a person or organization that resembles a machine (as in being methodical, tireless, or unemotional) **c** (1) **:** a combination of persons acting together for a common end along with the agencies they use (2) **:** a highly organized political group under the leadership of a boss or small clique

3 : a literary device or contrivance introduced for dramatic effect

Synonyms: engine, apparatus (a device for doing work beyond human physical, mental limitations);

Engine: usually used to indicate machines for transforming power;

Apparatus: more general than other words.

Clearly, this is a set of definitions that is both limiting in terms of the nature of a machine and confusing by perpetuating extension of the concept of machine to biological organisms and society—rather than indicating that such extensions are only analogies. On the other hand, Johnson's definition also encompasses the negative view of the term machine.

[3] The performance of simpler organisms, with "hard-wired" instructions is, in principle, more susceptible to complete definition than that of more complex organisms endowed with advanced brains. For these, will a limit be encountered beyond which their performance remains irreducibly unspecifiable?

[4] Only the instinctual use of simple machines drawn from the environment, such as a stick, may be viewed as genetic, although it may also have a learned component.

[5] For a survey of biological devices and designs see e.g., Vogel, 1988.

[6] The concept of telenomic level of a species—the quantity of information that must be transmitted, on average, by an individual to ensure reproductive invariance (Monod), has a parallel in machines in the information necessary to produce and reproduce a machine, that is in the level of detail of the design. An ability to transmit analogous design and construction information from machine to machine at that level is a key to machine self-reproduction.

[7] Gerald Estrin pioneered in 1970 the creation of computer chips that then rewire themselves to perform different functions.

[8] This does not exclude the possibility that some other higher organisms could possess something akin to an instinctive ethical sense.

[9] A capability to anticipate failure can be achieved by enabling the machine to monitor the conditions of its internal components as well as those of its environment.

[10] Evolution is a specific biological process. However, the term has come into general use to denote progression of ideas, designs, etc. It is employed here in that sense.

[11] However, even without the extremes of the delightfully whimsical ancient Chinese classification of animals cited tongue in cheek by Foucault in the preface of his *The Order of Things* (Foucault), classifications are always arbitrary, depending on their purpose and on the knowledge available at the time. Thus, the biologist's taxonomy of species, genus, family, class, order, created by Linnaeus in 1753, before any knowledge of evolution, is today not only obsolete, but also misleading (Donoghue, as reported by Pennisi).

[12] The 1996 sequencing of the genome of the Archaeon microbe "Methanococcus jannaschii" brings us closer to understanding what is universal to all life forms, and how these forms thus diverged (Bult et al.). This in turn may help in the evolution of biomimetic machines and of bio-machines.

[13] There could be separate branches for cast-iron concrete and steel frame buildings, as well as for composite materials construction.

[14] In the hammer, the kinetic energy imparted to it by the hand of the wielder is dissipated internally as heat and the head of the hammer transmits information about the stress to which it is subjected to the rest of the hammer by molecular action. However, in a passive machine these internal transformations or transmission of energy and information are incidental to the purpose of the machine.

[15] Conscious machines need to develop, through experience, preferential channels for communication among their various modalities, as well as an internal model of their environment. It has been proposed that the minimal requirements for consciousness are at least two "modalities," a sensor modality and a motor modality, plus an adaptive mechanism connecting the two. The function of that mechanism is to establish coherence between modalities and the environment, with the help of objective representations.

[16] To reiterate, the term *biosoma* has no other meaning than that of a shorthand notation for *bi*ology, *so*ciety and *ma*chines, and no connections to the various meanings of the word soma. Its adjective is: *biosomic*.

References

Bailey, Nathan, *A Universal Etymological English Dictionary*, R. Ware, London, 1730.

Billington, David P., *Robert Maillart's Bridges: The Art of Engineering*, Princeton University Press, Princeton, NJ, 1979.

Bugliarello, George (ed.), *Bioengineering, An Engineering View*, San Francisco Press, San Francisco, 1968.

Bugliarello, George, "Socio-Technology, a New Ideology and a New Methodology," *Engineering Education*, Vol. 63, No. 8, May 1973, pp. 580-582.

Bugliarello, George, "Rethinking Technology: Steady-State Earth or Biosoma," *World Development*, Vol. 1, No. 8, August 1973, pp. 45-51.

Bugliarello, George, "Biofluidmechanics: Quo Vadimus?" 1976 ALZA Lecture, *Annals of Biomedical Engineering*, Vol. 5, #3, Sept. 1977, pp. 209-247.

Bugliarello, George, "Merging the Artifact and Its Maker," *Mechanical Engineering*, Vol. 111, No. 9, September 1989, pp. 46-48.

Bugliarello, George, "Hyperintelligence: Humankind's Next Evolutionary Step," in *Rethinking the Curriculum Toward an Integrated, Interdisciplinary College Education*, M.E. Clark and S.A. Wawrytko, eds., Greenwood Press, New York, 1990, pp. 25-37.

Bugliarello, George, Namik K. Pak, Zhores I. Alferov and John H. Moore (eds.), *East-West Technology Transfer—New Perspectives and Human Resources*, Kluwer Academic Publishers, Dordrecht, 1996.

Bugliarello, George, "Telecommunications, Politics, Economics, and National Sovereignty: A New Game," *Airpower Journal*, Vol. X, No. 1, Spring 1996, pp. 6-17.

Bugliarello, George, "Urban Knowledge Parks and Economic and Social Development Strategies," *Journal of Urban Planning and Development*, American Society of Civil Engineers, New York, June 1996, pp. 33-45.

Bugliarello, George, "Rethinking Urbanization," *The Bridge*, E. 2001, Vol. 31, No.1, Spring 2001.

Bult, Carol J. et al., "Complete Genome Sequence of the Methanogenic Archaeon, Methanococcus jannaschii," *Science*, Vol. 273, 23 August 1996, pp. 1058-1073.

Burenhult, Goran (ed.), "The First Humans—Human Origins and History to 10,000 BC," Harper San Francisco, 1992.

De La Mettrie, Julien O., *L'Homme Machine*, Elie Luzac, Leyden, 1748.

De Tocqueville, Alexis, *Democracy in America*, Reprint edition, Knopf, April 1994.

Doolittle, W. Ford, "Phylogenetic Classification and the Universal Tree," *Science*, 294, No. 5423, June 25, 1999.

Florman, Samuel C., *The Existential Pleasures of Engineering*, St. Martin's Press, 1996.

Foucault, Michel, *The Order of Things*, Random House, 1970.

Freitas, R.A., Jr., and W.B. Zachary, "A Self-Replicating Growing Lunar Factory," in *Proceedings of the Eighth Princeton/AIAA Conference* (J. Grey and L.A. Hamdan, eds.) American Institute of Aeronautics and Astronautics, New York, 1981.

Givon, T. and Malle, B (Editors), *The Evolution of Language From Prelanguage,* John Benjamin, Amsterdam, 2003.

Hanson, Victor D., *The Western Way of War: Infantry Battle in Classical Greece*, University of California Press, February, 2000.

Hoffmann, Roald, "Molecular Beauty," *American Scientist*, vol. 36, p. 389, 1988.

Hunt, Gavin, "Crows in North Caledonia," *Nature*, January 15, 1996.

Huxley, Aldous, *Brave New World*, Harper & Row, New York, May 1976

Johnson, Samuel, *Dictionary of the English Language*, G. Long, England, 1755.

Kegan, John, *The Face of Battle,* Viking Press, 1995.

Kenner, Hugh, *The Mechanical Muse*, Oxford University Press, New York, 1987.

Kent, Richard A., "Timing Evolution Early Bursts," *Science*, Vol. 267, 6 January 1995, pp. 33-34.

Khaldun, Ibn, *An Introduction To History*, F. Rosenthal, translator, N.J. Dawood, editor, Bollinger Series, Princeton University Press, Princeton, NJ, 1969.

Knox, Bernard, *The Oldest Dead White European Males—and Other Reflections on the Classics*, Norton, New York, 1993.

Kranakis, Eda, *Constructing A Bridge*, MIT Press, Cambridge, MA, 1997.

Le Corbusier, *The City of Tomorrow and Its Planning*, (reprint) Dover, New York, 1987.

Lorenz, Konrad, *Die Acht Todsünden der Zivilisierten Menscheit*, Piper, München, 1973.

Maguire, G.Q., Jr. and Ellen M. McGee, "Implantable Brain Chips? Times for Debate," *Hastings Center Report*, 29, 1, Jan-Feb, 1999.

Malecha, Marvin J., *Form and Performance - Observations on the Amphitheater in Ancient Greece*, College of Environmental Design, California State Polytechnic University, Pomona, CA, 1991.

McLaren, Digby J., "Population Growth—Should We Be Worried?," *Population and the Environment*, Vol. 17, No. 3, Jan. 1996, pp. 243-259.

Merriam-Webster Dictionary On-line (2002).
http://www.m-w.com

Meier, Christian, "Athens—A Portrait of the City in its Golden Age," Metropolitan Books, Holt, New York, 1998.

Minsky, Marvin, "Conscious Machines," Free Speech Online, Blue Ribbon Company, August 13, 1998, http://kuoi.asui.vidako.edu/-kamikaze/documents/mirsky.html.

Monod, Jacques, *Chance and Necessity: an Essay on the Natural Philosophy of Modern Biology*, (translation), Knopf, New York, 1971.

Mumford, Lewis, *The City In History*, Harcourt Brace, 1968.

Pennisi, Elizabeth, "Evolutionary and Systematic Biologists Converge," *Science*, Vol. 273, July 12, 1996, pp. 181-182.

Penrose, Roger, "Shadows of the Mind: A Search for the Missing Science of Consciousness," Oxford University Press, April 1996.

Petroski, Henry, *To Engineer Is Human—The Role of Failure in Successful Design*, St. Martin's Press, New York, 1985.

Ramelli, Agostino, *The Various and Ingenious Machines*, [1558] Reprint Dover, New York, 1976.

Randall, John H., *The Making of the Modern Mind*, Houghton Mifflin, New York, 1940.

Rescher, Nicholas, *Satisfying Reason—Studies In the Theory of Knowledge*, Kluwer, Dordrecht, 1995 (see p. 168).

Ridley, Matt, *The Origins of Virtue—Human Instinct and the Evolution of Cooperation*, Viking Penguin, New York, 1997.

Roy, Rustum, "The Laws of 'STS' and the Laws of Science," *Bulletin of Science, Technology and Society*, Vol. 15, No. 1, 1995, pp. 1-2.

Ruse, Michael, *Philosophy of Biology Today*, State University of New York Press, Albany, 1988.

Takahata, N., Y. Satta and J. Klein, "Divergence Time and Population-Size in the Lineage Leading to Modern Humans, *Theoretical Population Biology*," 1995, Vol. 48, Issue 2, pp. 198-221.

Taylor, Henry O., *The Medieval Mind*, Harvard University Press, 1962.

Tomkins, Calvin, "Duchamp and New York," *The New Yorker*, Nov. 25, 1996, pp. 92-100.

Vogel, Steven, *Life's Devices—The Physical World of Animals and Plants*, Princeton University Press, Princeton, NJ, 1988.

Vogel, Steven, *Prime Mover—A Natural History of Muscle*, Norton, New York, 2002.

Von Neumann, John J. (edited posthumously by Arthur Burks), *Theory of Self-Reproducing Automation*, University of Illinois Press, Champaign-Urbana, 1966.

White, Lynn Jr., *Medieval Technology and Social Change*, Oxford, 1962.

Weber, Ernst with Frederik Nebeker, *The Evolution of Electrical Engineering—a Personal Perspective,* IEEE Press, New York, 1994.

Wilson, Edward O., *Sociobiology: The New Synthesis*, Bowker, 1975.

Wilson, Edward O., *Diversity of Life*, Harvard, Cambridge, MA, 1993.

Wilson, Edward O., "Consilience. The Unity of Knowledge," Knopff, New York, 1998.

Acknowledgements

These reflections stem from the opportunity afforded to me over the years by a variety of professional experiences to reflect on the interaction of biological organisms, societal organizations and processes and machines and on the meaning it holds for our future. I am most grateful to the great patience and helpfulness of my wife Virginia, to the intelligent and indefatigable work of Rose Emma, to the constructive critique of George Schillinger, to the reading and skillful editing reviews by Vlad Karas and Michelle Kerr, to the many who offered useful comments and suggestions and to the Sigma Xi, the Scientific Research Society, that gave me the opportunity as a national lecturer to present some of these reflections on a number of campuses.

About the Author

George Bugliarello, a *summa cum laude* graduate of the University of Padua, holds a Doctor of Science degree in Engineering from MIT, and several honorary degrees, and has been honored for the creation of MetroTech, the nation's largest urban university-industry park. He taught at Carnegie-Mellon's University, where he organized and chaired the graduate program in bioengineering, conducted extensive research in biological flows and designed, with his students, a computer language for water resources. He was dean of engineering at the new campus of the University of Illinois in Chicago. He is currently president emeritus at Polytechnic University in New York, where he previously served as president for 21 years and chancellor for nine years.

He is a member of the National Academy of Engineering and of the Council on Foreign Relations, a National Associate of the National Academies, and a founding member of the American Institute of Medical and Biological Engineering. He was president of the Sigma Xi, the scientific research society, and of the National Association of Science, Technology and Society, of which he is an honorary lifetime member.

He has been an Alza lecturer of the Biomedical Engineering Society, a Distinguished National Lecturer of the Sigma Xi and a chair of the Advisory Committee for the Selection of the National Medal of Technology, of the Advisory Committee for Science Education of the National Science Foundation, of the Board of Science and Technology for International Development and of the Board on the Infrastructure and Constructed Environment of the National Research Council.

He has published and lectured extensively, has founded and edits with George Schillinger *Technology In Society: An International Journal*, is interim editor-in-chief of *The Bridge*, the journal of the National Academy of Engineering, and in 2003, was elected Foreign Secretary of the National Academy of Engineering for a four year term.