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Biomedia

Abstract

Biology is the least developed natural science. With advancements in genetics the situation may radically change. The paper describes how existing technology can benefit from use of live systems. Genetically programmed live structures can be used in computer, electronic, chemical and medical engineering. Biological approach can revolutionize practically all areas of technology.

The paper is an attempt to specify both long-term and short-term goals of biotechnology. The long-term goals can be reached only after certain advancements in genetics, such as considerable improvement of speed and quality of gene reading (sequencing). The short-term goals are much more modest, but can be achieved at the current level of technological development.

The purpose of the paper is to attract attention to biotechnology as an excellent alternative to more commonly used technology of dead materials. The paper is not only a review of the ongoing work in the field, but also an attempt to formulate new ideas not found in the literature.

Live Computers

Our body consists of about 10^{13} live cells [1]. Each cell is an elaborate chemical computer. All cells have storage devices. The read-only genetic storage in each human cell holds about 1.5 Gbytes of data [2,3], which define how human body develops and functions. In addition cells have several different forms of temporary storage. Cells constructed so that they can interact with environment. Their senses include detection of heat, light, sound, presence of chemicals, or their own deformation. Their reactions to the input are changes of shape, color, viscosity, and electrical potential. The cell can make a copy of itself including a precise copy of its hardware and proofread gigabytes of genetic code in just a few minutes.

As in electronic computers it is possible to make a clear distinction between software and hardware in live cells. The separation of software and hardware is crucial in understanding how to program the system. The software layer in live cells is the genetic information recorded in chromosomes and mitochondrial DNA. The hardware is the rest of the cell. All multicelluar creatures on Earth share the same hardware design. We have single universal hardware platform. The software defines all the differences among creatures from jellyfish to humans.

The basic difference between live organisms and man-made creatures is an additional structural layer in the former. All higher life consists of unified cells. Man-made devices go directly from atoms to the final structure. One of the main advantages of cellular structure is regeneration, which means much higher stability. Each cell has a complete genetic information of the whole creature and can potentially rebuild the whole creature. The cellular structure solves problems of mechanical wearing and structural defects. The live cell can serve as a sensor, information processor, data storage or transmitter. The fine cellular structure allows living creatures to have a lot more sensors and information processing elements than any computer or robot created by people. Besides, genetic software makes the physical shape and structure programmable, while human-made systems can alter only their logical behavior.

Although computer networks seem similar to cellular constructions, cells in such systems are ridiculously big and have inconsistent spatial arrangement. The connection machine comes closer to live structure, but the cells in the connection machine are very primitive comparing to live ones. People only use network constructions for computational tasks. The live cells, on the other hand, do not only process information and control a construction, but also build a physical entity.

The desktop computer can hardly be compared to a whole live creature. By its complexity the computer seems closer to a clumsy single live cell. Unlike any living creature the computer is unaware of its physical surrounding and unable to move.

Genetic Programming

A trivial approach to genetic programming is to load information from chromosomes into the computer for modification, assemble new chromosomes, and implant them into a new cell [8]. The problem on this path is the current extremely low speed of gene reading. It would take about 20 genetic lab / years to read bit-by-bit a complete human genome [5,6]. The technologies to assemble amino-acid sequences are much faster.

The current state of genetics is very similar to that of chemistry before the discovery of the periodic law. The field lacks clear information classification. The knowledge in genetics is somewhat fragmented. A lot of work has been targeted at classification of genes [1] as large pieces of DNA without clear specification of their data structure and at low-level analysis of DNA sequences [2,6] for evolutional classification purposes.

Genetic engineering does not come close to what I mean by genetic programming. That part of biology semi-blindly shuffles pieces of DNA from existing life forms. It is inefficient in both acquiring knowledge about life and obtaining new useful features for created organisms.

A real breakthrough in biology will happen when the gene reading/writing is fast enough to go though the complete cycle of genetic data modification within days. From that moment on people will be able to extract and reverse engineer the software from many living creatures on our planet.

Live Organisms and Technology

The live organisms may be used as construction and information processing components in many areas of technology. Live systems can replace practically all our existing technology. However, an immediate replacement is impossible and unreasonable. Live technology can coexist and bind well with medical, electronic, chemical, and computer systems.

Currently the use of live organisms is limited to food industry and medicine [4,8]. People use plants, animals, and bacteria that already exit in nature. Modifications are limited to breeding. Which means that no new features can be consciously added, only a limited set of preexisting properties of the organisms can be combined or enhanced.

One possible objection to biotechnology is that it is messy. But in fact almost all technologies we are dealing with are messy at some point. For example, batteries, which are now everywhere, contain highly toxic liquids and metals inside. Electronics production requires many cycles of messy processes. People themselves are messy in exactly the same way as biotechnology. Wherever we are we require food, heat, water, and sewage disposal. Our devices do not use food, heating, watering, and disposal systems. They stick with electricity, which we do not really need for ourselves.

Electronics

Biotechnology can bind quite well with computer engineering. Live cells can be used in storage devices. Each live cell can hold gigabytes of information, be just a micron in diameter, and replicate itself with all the data in seconds. The obstacle is again the reading/writing technology.

Live cells can revolutionize display technology replacing transistors and tricky wiring. Live cells can change colors and rapidly transfer signals. In addition they can solve the problem of screen defects. Cells can regenerate, so that a scratched or shattered display will be able to repair itself.

Live cells are efficient energy converters. They can, for example, use chemical compounds, such as sugars, as a source of energy and convert it to mechanical energy, heat, light, or even directly to electricity. Algae and plants use light to produce chemical compounds necessary to sustain life.

Cells can even replace batteries. One way is to clone cells from electric eels. Another way is to make bacteria recycle chemicals inside a regular battery. Biobatteries would probably require sugar instead of charging.

One of the advantages of biotechnology is that it can always be ecologically clean. For example, a material made of live cells can decompose itself when disposed.

The human brain obviously has quite impressive processing power. One possible application of biotechnology is to construct new computers based on neural structure of animals. Such computers can either be independent or linked to conventional electronic systems.

Live cells can serve as sensors for a regular computer. Live cells can provide a lot of useful information about environment. Besides they can form fine sensing grids and transfer sensor information as electric impulses to the point where a computer can capture them. That can significantly improve video technology. Live cells can provide tactile information. Computers can receive signals from neurons of people or other creatures [7] and give feedback directly to the neural net.

Live systems can change their shape. They can be used as tangible output or 3D displays. Cells programmed to grow into necessary shapes can replace clay, mills, and moldings. Besides, living cells can form a necessary internal structure.

Medicine

Contemporary medicine can only assist our body in curing itself. Most of the medical remedies are based not deep knowledge of what is really going on, but on random experimental results. Biotechnology can help medicine to understand how human body works and how to cure diseases.

People started replacing natural body parts since the ancient times. Ancient Egyptians are known to have used dental implants. Today more than 11 million Americans have at least one medical implant. These implants include fixation devices used to assist healing of fractures, lens implants, artificial joints, heart pacemakers, and artificial heart valves. Medical device implants is one of the most promising areas of medicine. However, many plants and animals have an ability to regenerate some of their organs. Skin of almost all creatures including humans can grow back when damaged.

Tails, legs, and even eyes of various amphibians and reptiles grow back when lost in a battle or accident.

I think that instead of putting on eyeglasses or putting in contact lenses we may actually try to tell our eyes to change their shape a little. Or instead of drilling damaged teeth we may try to grow new ones. As soon as we know better the genetic code that controls our body, we will be able to heal many serious deceases and mutilations without use of surgery and dead medical implants. Instead of transplanting organs people will be able to grow new ones. Scientists are already trying to alter genetic code of some cells of human body [8]. Unfortunately all those techniques will not be very helpful until the genetic code is fully understood.

Medicine does not know how to kill viruses. Our body does. The only exception is AIDS. That is why it is such a trouble. With assistance of genetic programming medicine may be able to assemble antibodies to destroy viruses.

Chemistry

Live cells are chemical computers. They can assemble and modify molecules. If we knew how to program them we would have a very efficient way to produce many chemicals compounds and materials.

Bacteria are already widely used in food production [4]. But genetic programming may open completely new ways to make food. Instead of a long production cycle of growing plants, extracting grain, milling, the new technology may be able to produce necessary food components in a factory.

Building materials can also be replaced with live matter. The advantages are again regeneration and ecological cleanness. Wood has always been one of the best building materials because of the excellent combination of physical properties. But wood is stems of dead trees. What if we could use live cells instead of dead? Buildings could repair minor damages, heat or cool themselves without additional appliances, and even change their size and shape.

Biotechnology vs. Nanotechnology

With nanotechnology [9] we would have to build hardware from scratch and try to make it programmable. Nanotechnology as such does not exist. Living creatures are everywhere. Nanotechnology would consume a lot of human efforts because everything has to be implemented and debugged from scratch. Life, on the other hand, would provide us with ready-to-use programmable hardware and a huge library of ready-to-use engineering and programming solutions in the form of various living creatures. Reverse engineering is much faster than engineering.

Ideal conditions for nanotechnology [9] are very low temperatures and absence of oxygen, water, and other chemically active compounds, which is very different from our normal environment where life can exist. So, to use nanotechnology we may need to create a separate environment for it.

One of the hardest problems for nanotechnology would be to defend the nanoconstructions from life. The live organisms are quite aggressive and highly adaptable. They will use the nanoconstructions as a place to live or as food. The living creatures have a long history of adaptation to new conditions. It would be hard to beat their ability to conquer new territories and eat everything.

Biotechnology and Reverse Engineering

Biotechnology cannot develop without broad use of reverse engineering. Biotechnology is completely different from any other technologies people created because many live creatures and systems already have excellent engineering solutions. It is the only field where people do not have to invent and build everything from scratch. Nature has spent a few billion years shaping up the life forms. It would be unwise to ignore the knowledge accumulated in genes of living creatures. So far reverse engineering has not attracted enough serious attention because it is often regarded as stealing of knowledge obtained by other people. In biotechnology nobody has the right to claim a patent for any solution existing in nature.

Regular scientific or engineering approach is not efficient in reverse engineering. The purpose of science is to get as much knowledge about a subject as possible. The purpose of engineering is to find an efficient solution based on deep and broad knowledge about the subject. Efficient reverse engineering recreates a solution or finds necessary information avoiding as many insignificant details as possible.

Today computer engineering is quite young. It is possible to find people who designed almost any existing computer or program and ask them how that thing works. In the future, however, recovering old databases or fixing old software may become problematic. The only possible solution will be reverse engineering.

Biology and the Media Lab

Biology is probably the only big part of science and technology not covered by the Media Lab. In the future genetics will certainly become more common and migrate from the biolab to the computer desktop. Computers are already powerful enough to process genetic information, but unfortunately the technology for gene manipulation lags behind.

Many research projects can benefit from better exploration of biotechnology. Although using dead materials is somewhat safer and less challenging, if we really want to invent the future we must pay more attention to biology.

The research on electronic paper can use the features of live cells to reach its goal. I propose to use live bacteria as active elements in electronic paper. Joe Jacobson tried to use organic chemical compounds extracted from live cells in his research. Unfortunately the compounds do not change colors as efficiently outside the cell as they do inside. Many live creatures, such as chameleons, octopuses, and some bacteria, can change colors very rapidly and with minimal energy consumption. The live cells can also store large amounts of information in chromosomes, so that the electronic paper device may not require any additional data storage components. Manufacturing of a live paper may be as easy as taking one of the cells from an existing display and placing it to a new frame filled with sugar and water mixture to support life.

Live cells are small enough to work in holographic displays. They can change their optical properties depending on external stimuli. There are four possible uses of the live cells in video or holographic process. The first is to use live cells to form organic photoemulsions. In this case the cells die before the actual photo process. The second is to use live cells as the photoemulsion. In this case the cells die after the photomaterial is exposed to light. The third option is to use live cells instead of CCDs. In this case cells stay alive all the time detecting the light and sending signals to the processing system. The fourth is to use live cells as active video output elements. The cells would stay alive and change their optical properties according to their internal programming or signals from the processing system.

I would like to build batteries, which use bacteria to convert chemical energy to electricity. I believe it can be done even without fundamental genetic alterations. Several possible approaches to building biobatteries are recycling chemicals produced by conventional batteries using bacteria to prolong battery life, chemical battery recharging, cloning electricity-generating cells of electric eels.

Many unusual sensors can be created with bacteria. The computer can analyze changes in optical or electric properties of some bacteria or somatic cells to detect pressure, temperature, or chemical composition of environment. It may be possible to grow networks of tactile sensors to cover the surface of an electronic device.

Another interesting use of living creatures, which does not even require any advancements in biology, is to track behavior of domesticated animals with a computer to automatically obtain information about environment. For example, the position and physiological parameters of a dog may provide the computer with important information about what is going on in the house. A dog or another animal may carry a small computer, which will give the dog commands and analyze information from various sensors. This cyberdog combination can perform many tasks that could not be done by a computer, robot, or dog alone. For example, such a cyberdog can carry a camera to a place unreachable to people or robots, track people or objects by the smell much faster than a dog-human combination, and inform the police about a break-ins. Dogs with wearable computers can also be human partners in computer games or play an active role in virtual environments.

The live systems have outstanding features in terms of physics of information processing [11]. They manage to use minimal energy to load, save, and duplicate information recorded in DNA and other chemical compounds. Although live cells perform direct information manipulations slower than contemporary electronic microprocessors, they are much smaller, spatially consistent, and energy efficient. It may be easier to create complex parallel structures with live cells than with electronic devices.

The Media Lab can contribute many ideas to biology and genetics. As a multidisciplinary institution the lab can discover totally new approaches based on biology in many fields of technology.

References

1. An introduction to genetic analysis. / Anthony Griffiths [et al.] 1993
2. Molecular evolutionary genetics. / Masatoshi Nei 1987
3. Role of excessive genetic information in evolution. / Vadim Gerasimov 1995
4. Wisconsin's Biotechnology and Food Handbook / Tom Zinnen and Jane Voichick
5. Human Molecular Genetics / Weber, W. and Wong, C. 1993
6. Molecular Evolution: Computer Analysis of Protein and Nucleic Acid Sequences. / R. F. Doolittle 1990
7. Controlling Computers with Neural Signals/ Hugh S. Lusted and R. Benjamin Knapp, Scientific American October 1996
8. Making Gene Therapy Work, Special Report, Scientific American June 1997
9. Nanosystems : Molecular Machinery, Manufacturing, and Computation / Eric K. Drexler 1992
10. Animal Cell Biotechnology / J.B. Griffiths (Editor), R. E. Spier 1994
11. Signal entropy and the thermodynamics of computation / Neil Gershenfeld 1996