Is Life Analog or Digital?

by Freeman Dyson

One of my favorite books is *Great Mambo Chicken and the Transhuman Condition"* by Ed Regis. The book is a collection of stories about weird ideas and weird people. The transhuman condition is an idea suggested by Hans Moravec. It is the way you live when your memories and mental processes are down-loaded from your brain into a computer. The wiring system of the computer is a substitute for the axons and synapses of the brain. You can then use the computer as a back-up, to keep your personality going in case your brain gets smashed in a car accident, or in case your brain develops Alzheimer's. After your old brain is gone, you might decide to upload yourself into a new brain, or you might decide to cut your losses and live happily as a transhuman in the computer. The transhumans won't have to worry about keeping warm. They can adjust their temperature to fit their surroundings. If the computer is made of silicon, the transhuman condition is silicon-based life. Silicon-based life is a possible form for life in a cold universe to adopt, whether or not it happens to begin with water-based creatures like us made of flesh and blood.

Another possible form of life is the Black Cloud described by Fred Hoyle in his famous science fiction novel. The Black Cloud lives in the vacuum of space and is composed of dust-grains instead of cells. It derives its energy from gravitation or starlight, and acquires chemical nutrients from the naturally occurring interstellar dust. It is held together by electric and magnetic interactions between neighboring grains. Instead of having a nervous system or a wiring system, it has a network of long-range electromagnetic signals that transmit information and coordinate its activities. Like silicon-based life and unlike water-based life, the Black Cloud can adapt to arbitrarily low temperatures. Its demand for energy will diminish as the temperature goes down.

Silicon-based life and dust-based life are fiction and not fact. I use them as examples to illustrate an abstract argument. The examples are taken from science-fiction but the abstract argument is rigorous science. The abstract concepts are valid, whether or not the examples are real. The concepts are digital-life and analog-life. The concepts are based on a broad definition of life. For the purposes of this discussion, life is defined as a material system that can acquire, store, process, and use information to organize its activities. In this broad view, the essence of life is information, but information is not synonymous with life. To be alive, a system must not only hold information but process and use it. It is the active use of information, and not the passive storage, that constitutes life.

The two ways of processing information are analog and digital. An LP record gives us music in analog form, a CD gives us music in digital form. A slide-rule does multiplication and division in analog form, an electronic calculator or computer does them in digital form. We define analog-life as life that processes information in analog form, digital-life as life that processes information in digital form. To visualize digital-life, think of a transhuman inhabiting a computer. To visualize analog-life, think of a Black Cloud. The next question that arises is, are we humans analog or digital? We don't yet know the answer to this question. The information in a human is mostly to be found in two places, in our genes and in our brains. The information in our genes is certainly digital, coded in the four-level alphabet of DNA. The information in our brains is still a great mystery. Nobody yet knows how the human memory works. It seems likely that memories are recorded in variations of the strengths of synapses connecting the billions of neurons in the brain with one another, but we do not know how the strengths of synapses are varied. It could well turn out that the processing of information in our brains is partly digital and partly analog. If we are partly analog, the down-loading of a human consciousness into a digital computer may involve a certain loss of our finer feelings and qualities. That would not be surprising. I certainly have no desire to try the experiment myself.

There is a third possibility, that the processing of information in our brains is done with quantum processes, so that the brain is a quantum computer. We know that quantum computers are possible in principle, and that they are in principle more powerful than digital computers. But we don't know how to build a quantum computer, and we have no evidence that anything resembling a quantum computer exists in our brains. Since we know so little about quantum computing, I do not consider it in this discussion.

I started thinking about the abstract definition of life twenty years ago, when I published a paper in Reviews of Modern Physics about the possibility that life could survive for ever in a cold expanding universe. I proved to my own satisfaction that survival is possible for a community of living creatures using only a finite store of matter and energy. Then, two years ago, Lawrence Krauss and Glenn Starkman, friends of mine at Case Western Reserve University in Cleveland, sent me a paper with the title "Life, the Universe, and Nothing". They say flatly that survival of life for ever is impossible. They say that everything I claimed to prove in my Reviews of Modern Physics paper is wrong. I was happy when I read the Krauss-Starkman paper. It is much more fun to be contradicted than to be ignored.

In the two years since I read their paper, Krauss and Starkman and I have been engaged in vigorous arguments, writing back and forth by E-mail, trying to pokes holes in each others' calculations. The battle is not over, but we have stayed friends. We have not found any holes that cannot be repaired. It begins to look as if their arguments are right, and my arguments are right too. We can both be right because we are making different assumptions about the nature of life. It turns out that they are right, and life cannot survive for ever, if life is digital, but I am right, and life may survive for ever, if life is analog. This conclusion was unexpected. In the development of our human technology during the last fifty years, analog devices such as LP records and slide-rules appear to be primitive and feeble, while digital devices are overwhelmingly more convenient and powerful. In the modern information-based economy, digital wins every time. So it was unexpected to find that under very general conditions, analog life has a better chance of surviving than digital life. Perhaps this implies that when the time comes for us to adapt ourselves to a cold universe and abandon our extravagant flesh-and-blood habits, we should upload ourselves to black clouds in space rather than download ourselves to silicon chips in a computer center. If I had to choose, I would go for the black cloud every time.

The superiority of analog-life is not so surprising if you are familiar with the mathematical theory of computable numbers and computable functions. Marian Pour-El and Ian Richards, two mathematicians at the University of Minnesota, proved a theorem twenty years ago that says, in a mathematically precise way, that analog computers are more powerful than digital computers. They give examples of numbers that are proved to be non-computable with digital computers but are computable with a simple kind of analog computer. The essential difference between analog and digital computers is that an analog computer deals directly with continuous variables while a digital computer deals only with discrete variables. Our modern digital computers deal only with zeroes and ones. Their analog computer is a classical field propagating though space and time and obeying a linear wave equation. The classical electromagnetic field obeying the Maxwell equations would do the job. Pour-El and Richards show that the field can be focussed on a point in such a way that the strength of the field at that point is not computable by any digital computer, but it can be measured by a simple analog device. The imaginary situation that they consider has nothing to do with biological information. The Pour-El-Richards theorem does not prove that analog-life will survive better in a cold universe. It only makes this conclusion less surprising.

The argument of Krauss and Starkman is based on quantum mechanics. If any material system, living or dead, is finite, it will have only a finite set of accessible quantum states. A finite subset of these states will be ground-states with precisely equal energy, and all other states will have energies separated from the ground-states by a finite energy-gap. If the system could live for ever, the temperature would ultimately become much lower than the energy-gap, and the states above the gap would become inaccessible. From that time on, the system could no longer emit or absorb energy. It could store a certain amount of information in its permanently frozen ground states, but it could not process the information. It would be, according to our definition, dead. Krauss and Starkman thought they had dealt a fatal blow to my survival strategy with their argument. But I am still on my feet, and here is my rebuttal. Their argument is valid for any system that stores information in devices confined within a volume of fixed size as time goes on. It is valid for any system that processes information digitally, using discrete states as carriers of information. In a digital system, the energy gap between discrete states remains fixed as the temperature goes to zero, and the system ceases to operate when the temperature is much lower than the energy gap. But this argument does not apply to a system based on analog rather than digital devices. For example, consider a living system like Hoyle's Black Cloud, composed of dust-grains interacting by means of electric and magnetic forces. After the universe has cooled down, each dust-grain will be in its ground-state, so that the internal temperature of each grain is zero. But the effective temperature of the system is the kinetic temperature of random motions of the grains. Since electric and gravitational energies vary inversely with distance, the cloud must expand as its temperature cools. A simple calculation shows that, in spite of the falling temperature, the number of quantum-states accessible to each grain increases with the three halves power of the size of the cloud. The number of quantum-states grows larger and larger as the cloud expands. In an analog system of this kind, there is no ground state and no energy gap.

An analog form of life, such as Hoyle's black cloud, adapts better to low temperatures, because a cloud with a fixed number of grains can expand its memory without limit by increasing its linear scale. The quantized-energy argument does not apply to an analog system, because the number of quantum-states is unbounded. At late times quantum mechanics becomes irrelevant, and the behavior of the system becomes essentially classical. The number of quantum states becomes so large that classical mechanics becomes exact. When analog systems work classically, the quantized-energy argument fails. That is why survival is possible in the domain of classical mechanics although it is impossible in the domain of quantum mechanics. Fortunately, classical mechanics becomes dominant as the universe expands and cools. But Krauss and Starkman have not yet conceded. I am still expecting them to come back with new arguments which I will then do my best to refute.

It seems to me now that the question, whether life is analog or digital, is more interesting and perhaps more important, than the question of ultimate survival out of which it arose.