Reflections of a Communication Engineer*

MARCEL J. E. GOLAY†, FELLOW, IRE

In March, of this year, the American Chemical Society heard an address by the recipient of its Sargent Award in Chemical Instrumentation. The recipient, however, was not a chemist; he was a communication engineer, IRE Fellow, and holder of the Harry Diamond Memorial Award. And he did not speak on chemistry. Indeed, his remarks were so thought provoking and of such broad interest to PROCEEDINGS readers that the text has been reprinted below from the ACS journal *Analytical Chemistry*.
—*The Editor*

I CANNOT TELL A LIE—I am not a chemist. That is why I have decided to change the subject of my talk. Others will tell you, more competently than I could, about the physical chemistry of chromatography. It is as a communication engineer that I will talk to you. And if the things I say increase in strangeness as I go along, I will ask you to remember two things.

The first is this: Many of the recent advances in science are due to the cross-fertilization of, at first view, separate and distinct fields.

And the second is this: Of all the disciplines guilty of such fruitful incests, communication engineering is the guiltiest of them all, with its inroads in physics and chemistry, in biology, in sociology through automation, in philosophy through information theory. Communication engineering—or should I say communication philosophy—appears as an octopus, with its tentacles stirring thought here, there, and everywhere, an octopus intimately linked to the development of social man, and to the reflections of individual man.

I owe the good fortune of being with you today to the accident of having noted that, in a simplified form, the chromatographic partition process could be described by the telegrapher's equation. Nothing more would have happened if my friends at The Perkin-Elmer Corp. had not asked me to stick numbers in the equation—after all, a consultant must earn his keep. This led to the finding that the packed chromatographic column of five years ago had a basic efficiency, as measured by the Performance Index, of around 0.01 per cent. This finding led in turn to the idea of making a column which had the form of the simple model adopted for the theoretical study—namely, an open tube coated with a retentive layer. That is all.

I said I would talk as a communication man about communication philosophy and the strange lands where it may take us. It is not every day that I have the opportunity of addressing a kindly inclined and nearly captive, well guarded audience about my extracurricular thoughts, and I will start with a reminiscence. I will reminisce about a time when I was a little boy, going shopping with my mother, walking alongside, and trying to digest something metaphysical I had read, which I was probably too young to read. Yet all of a sudden, all my thoughts came into a focus, and I started to speculate: Suppose there had been nothing at all, no time, no space, no matter, no people. But there is something and I am part of this something, playing my role in it. There was rain falling on the pavement on that day and I remember that, too.

Surely the simple thought that there is a universe and that we should not be indifferent to our privilege of playing our part in it has been the underlying incentive to the building and the evolution of our philosophy and cosmology.

The beginnings of our cosmology appear naive in retrospect. Some of you may recall learning in your history class about the early mythological world, flat and carried by a large elephant, with his feet on four turtles swimming in a sea of milk. Little by little these notions became purified. We made a notable step forward when we accepted a universe not centered in our little earth. For a long time the concepts associated with the origin of our universe oscillated between an instinctive belief in a beginning, a creation, and a scientific opinion that we lived in a static universe with time stretching indefinitely backwards and forwards. And then, last century, budding physical chemistry led us to a real difficulty.

It was in the early part of the last century that Carnot formulated what became accepted as the second law of thermodynamics. As further developed by Helmholtz, this law stated, in effect, that there is a continuous degeneracy, a continuous decay of energy. You can mix hot and cold water, but you cannot unmix them.

When you extend this principle to our whole universe —and it is the virtue of any principle that you can do

* Reprinted with permission of the American Chemical Society from *Analytical Chemistry*, vol. 33, pp. 23A–31A; June, 1961.
† Consultant, The Perkin-Elmer Corp., and the Philco Corp., 116 Ridge Road, Rumson, N. J.

so with it—you come to the metaphysical conclusion that this irreversibility of nature's processes demands that there be a definite beginning, a creation. But the semireligious concept of a creation, with the corollary concept of a Creator, was scientifically inadmissible, so it was thought, and matters stayed in that impasse through three generations of scientists. In order to get out of this difficulty, as able a philosopher as Poincaré made intellectual somersaults worthy of a devil caught in the holy fonts. He surmised, for instance, that if time marched forward in one part of the universe, this was made up by time going backward in some other regions, which is, of course, inadmissible. The clock cannot run backward.

Static Universe Concept Is Untenable

Things were in this impasse when two additional discoveries, taken together, made the concept of a static, uncreated universe completely untenable. The first was the discovery of radioactivity. Many natural radioactive isotopes such as thorium, uranium, and potassium have a very low rate of decay, and the fraction remaining today establishes a rough epoch for their creation, of the order of several billion years ago.

The second discovery was made by the astronomer Hubble in an entirely different domain. Hubble observed that many large galaxies are receding from us at a high speed. Galaxies are assemblies of from a billion to a quadrillion stars, and as they recede from us their characteristic color is shifted towards the red. Hubble observed that the farther the galaxies, the greater the red shift. But we are not in the center of the universe. The universe has no center in the sense that an orange has a center. Thus every galaxy must be receding from every other. This can only mean that we have a general explosion, and Hubble calculated that galaxies receded from each other as if this general explosion started at roughly the same epoch already determined by a study of the rate of decay of our radioactive minerals.

It was a Belgian cleric, the Abbé Lemaitre, who cut the Gordian knot by saying: "Let us postulate that the whole universe started several billion years ago with a single enormous atom." And it turned out that his daring hypothesis led to fewer difficulties than any other. This is the decisive test of any physical theory. The postulate of Lemaitre is generally accepted today, and you will find in the scientific literature quite serious speculation as to the state of the universe two minutes after its creation, for instance.

You may well ask: But what was there before and why did it all start? And of course, the question remains unanswered.

You may well ask also: Did it start with a pinpoint of matter of no size and infinite density? This is an interesting question to think about, for the following reason. When we permit two masses to come together by gravitational attraction, like a mass of water falling towards the earth center through a hydroelectric plant, we derive useful energy at the expense of the negative gravitational potential energy of these two masses. And when we calculate the total negative gravitational energy for the entire universe, using available astronomical data, we find that it is of the order of magnitude of the total positive energy in the form of masses, radiation, kinetic energy, and so forth. So we are led to ask: Could it be that the total energy of the universe is actually zero, that the positive energy we have in the form of mass and radiation is merely the result of a trade for negative gravitational energy? Then, if this is so, perhaps the Creator did not require the enormous mass of all the stars that we see, but required merely the intelligence to trigger the process, after which it kept going. We shall come back to this, but let us, for the time being, remember that some ten billion years ago a quite extraordinary event took place, beyond which the veil of history is forever closed to us.

First Protozoic Life

Now let us look at another historical puzzle, of a completely different order. Some two billion years ago, when our universe was already several billion years old, another extraordinary event took place on this earth. It was nothing as spectacular and grandiose as the creation of our macrocosm. It was microscopic in nature, but may turn out to be the most significant thing in the history, not of just our little earth, but of our entire universe. I refer, of course, to the appearance of the first protozoic life. After its creation, life evolved, and culminated in the appearance of man. Last century this process of evolution, especially in its last stages, was a subject of debate and controversy. Much ado was made about missing links, but today we think we understand better this evolution process, and why few ancestral forms, not just of man, but of most living creatures, are ever found. What we do not understand is the very beginning of the process: what produced this first molecule? We may be tempted to be superficial and shrug off the question by saying that the first living molecule was produced by chance, but let us give this problem a second look, in the light of information theory.

New Discipline-Information Theory

Information theory is a recent addition to our family of disciplines and it deals with a subject which is closely related to the second law of thermodynamics, the very law which states that the passage of time is marked by a decay of energy, and hence that there must have been a beginning to our universe. In many respects information theory constitutes that chapter of communication theory which has had, and will continue to have, an impact on metaphysics and philosophy.

The beginnings of information theory are curious. Nearly a century ago Maxwell expressed his impatience with the second law of thermodynamics by inventing a little demon, Maxwell's demon, which was to haunt two generations of scientists. As you know, Maxwell's demon is perched by a trapdoor in a wall separating two identical gas masses, and every time a molecule comes from the first gas mass in the direction of the trapdoor he opens it for an instant and lets that molecule pass through to the second gas mass. After a while you have more molecules and more gas pressure in the second gas mass than in the first, and that extra gas mass can expand into the first and produce useful work, while cooling. This constitutes a violation of the second law because useful work has been obtained from the heat of two gas masses originally in temperature and pressure equilibrium. A good paradox deserves a good answer, and a clever demon deserves a clever exorcism, and it was not until 1929 that this was done by the physicist Szilard, who said that Maxwell's demon cannot operate, because he does not have the information as to when to open his trapdoor.

For some 15 years Szilard's article remained unappreciated by almost everyone, including Szilard himself. His original manuscript had been noticed on his desk by friends, who persuaded him to let them mail it to their scientific journal; otherwise it might have remained unpublished. But shortly after the last war, certain statistical aspects of the theory of communication became of interest simultaneously to several researchers. In 1948 Shannon published his classic article, which became the foundation of information theory. In this article he noted the similarity between the entropy of the thermodynamicist and the negentropy of information. If you will pardon a personal reference, I heaped the last indignity on the poor demon when I showed that even with the most efficient transmission system, the energy required to communicate to the demon the information he needs would at least equal the useful energy he could retrieve by operating his trapdoor. So, even if the information the demon needed were available at no cost, it could not be communicated to him, without destroying his raison d'être.

I am talking at length about information theory because of the dualism between the second law and information theory on the one hand and the dualism between the creation of the universe and the creation of life on the other hand. It is information theory, and the new scientific attitude produced by information theory, which has revealed some interesting aspects of living molecules and living cells.

Information theory has taught us how to deal quantitatively with structure, with pattern, with what the Germans call Gestalt. There is even speculation about the admission of beauty and esthetics to the community of scientific concepts by information theory.

We can place within the scope of information theory the following problem, which was examined by the mathematician Von Neumann. Suppose we wanted to build a machine capable of reaching into bins for all of its parts, and capable of assembling from these parts a second machine, just like itself. What is the minimum amount of structure or information which should be built into the first machine? The answer came out to be of the order of 1500 bits—1500 choices between alternatives which the machine should be able to decide. This answer is very suggestive, because 1500 bits happens to be also the order of magnitude of the amount of structure contained in the simplest large protein molecule which, immersed in a bath of nutrients, can induce the assembly of these nutrients into another large protein molecule like itself, and then separate itself from it. That is what the process called life consists of, and unless and until we discover a new process in which simpler molecules have semilife properties, the inquiry into the birth of life can be reduced to an inquiry into the possibility or probability of the spontaneous assembly of such a molecule, out of a bath of its essential constituents. And this is exactly where we run into an interesting difficulty.

Spontaneous Creation of Life?

By making the most favorable assumptions as to the conditions in which this spontaneous creation of life could have occurred on this earth, we do not come anywhere near the spontaneous assembly of 1500 bits; we can account for perhaps one-tenth that number. Do not shrug this off as being only one order of magnitude off. This involves a factor of 10 in the exponent, and there is a vast difference between the probability of 1 part in 2^{150} and 1 part in 2^{1500}. Then you might say: But it could have happened in many places in our universe, and if it had not happened here, we would not be here to talk about it.

Very well, multiply 2^{150} by the number of stars—that is, by the number of potential solar systems, in the universe—and you obtain 2^{220}, still short of the mark. And yet, life did begin, and looking back in time, we see two mysteries, or at least two highly unlikely events. The first, the creation of the universe, of space, of time, of matter. The second, the creation of life, from which we evolved as a matter of course almost, with such unlikely beings as chemists and engineers in our midst, producing in the laboratory improbable assemblages such as a liter of liquid helium, or saying such unlikely things as what I am now saying to equally unlikely assemblies of molecules as my listeners. We may even have some day an unlikely biochemist who will assemble, radical by radical, an unlikely large molecule which can reproduce itself. But this would not resolve the historical mystery of the creation of the first living molecule.

Two Big Questions of the Future

All I have said so far has been to prepare the ground for two big questions, dealing with what could be called the two basic mysteries of the future.

The first big question is philosophical, and can be stated fairly simply. With his intelligence, with his ability to make experiments and to process information, does man have the potentiality of ever acquiring full information about the basic laws of our physical universe?

I am sure all of us have asked ourselves this, or a similar question. Some of us believe that the final answer will always escape us, even though every discovery, every extension of present physical theory brings us closer to it. Others of us believe that when we run into integral numbers, such as the number of protons and neutrons in a nucleus, we are approaching the ultimate physical knowledge.

Tied to this first big question, there are other tempting questions. For instance, we have an information theory which has established a measure for the amount of information we can communicate to each other. To be sure it is a brutal measure. To gauge meaningful information in terms of bits—the bits of information Maxwell's demon lacks—would be as meaningless as evaluating a work of art with a yardstick or a weight scale. All the information contained in all the books of the world, some 2^{60} bits, would not suffice for the separation of one milligram of air into its slow and fast molecules, and the information content of a thoughtfully filled time capsule would not suffice for a picogram. Hemmed in as we are by finiteness—the surmised finiteness of our universe, of our brain cells, of our thoughts, and of our life span—we strive for infinitude in the higher values, the intellectual, artistic and spiritual values. We are loath to admit the possibility of a measure of these, and would welcome a proof of the impossibility of such a measure. Should we, some day, have a measure of intelligence, or will intelligence always transcend a definition of itself? And even if we succeed in defining and measuring intelligence, may we eventually prove mathematically the impossibility of intelligence reaching the ultimate truth, just as the mathematician Godel has proved the existence of undemonstrable theorems and the openness, the infinitude of number theory? Shall we perhaps come to the paradoxical proposition that a supreme intelligence should disprove the possibility of its very existence?

I do not want to linger on these speculations, no matter how fascinating they may be. I want to come to the second big question.

While we do not know whether or not we shall be able some day to unravel the last shred of mystery surrounding the truth of the universe we live in, we do know, from the second law of thermodynamics, that the clock cannot run backward, and that our universe is condemned to eventual total decay, to end, as T. S. Eliot has put it, not with a bang but with a whimper. Shall we sit helplessly by watching that process, until even the modest wants of life as we know it can be no longer supplied?

Alternatively, is there a possibility that human intelligence will have the capability of doing something radical about the situation?

At first glance, the answer would seem to be "no"; the second law drives the universe inexorably to eventual decay, and regeneration is ruled out. It is at this point that I would interject a very timid "but." Remember that the world may well have been triggered into existence by a highly intelligent act producing a highly unlikely event—remember that the total energy of the universe may be very small, maybe even zero, the creation of mass having proceeded at the expense of negative gravitational energy. Could it become man's role to be the author of a similar highly intelligent act, before the clock of his universe becomes unwound?

Matter-Negative Gravitational Energy Exchange

I admit this sounds fantastic, because we have today no inkling of the mechanism involved in any trade of positive energy in the form of matter for negative gravitational energy. I must ask you to remember that, so far, physicists have not succeeded in performing a single experiment which connects gravitational phenomena with electrical phenomena, because electrical forces between elementary particles are some 40 orders of magnitude larger than gravitational forces. We are, therefore, at the point where metaphysical arguments must take over from physical arguments. That is, we may assume yet undiscovered mechanisms, while being careful not to violate already established physical principles.

I have pointed out before that we, men, these highly unlikely but intelligent creatures, have produced such unlikely things as a liter of liquid helium, something never produced spontaneously before anywhere in our universe.

Suppose now that our colleagues, the nuclear chemists, were to succeed in engineering a relatively heavy neutral particle, of extremely small volume, and of extremely low probability of spontaneous generation, just like the liter of liquid helium. Keep on supposing that this new particle has sufficient interaction with ordinary matter as we know it, and once produced in some supercosmotron, trickles gently toward the center of the earth, where it coalesces with others like itself into a very small mass of extraordinarily high density. The manufacture of these particles continues, and in a little while this small mass has the size of an electron. Later on, after many more particles have been produced and assembled, this small mass acquires the size of a molecule. But this is an important project, and several million years later (there is a cooling problem) a few millionths of our earth mass have been thus transformed and poured in the ground, to reassemble in the earth's center into a tiny sphere, one wavelength of light in diameter. Some very interesting things could begin to happen by then. Remember that space is curved by mass. Oh, very little. But on the mass surface, this effect is in inverse proportion to the radius of that mass. And I have postulated a very, very small size of extraordinarily high density. By the time our small but enormously heavy mass has reached a wavelength of light in diameter, it has almost wrapped its own space around itself, and has become very close to what I would call a gravitational "crit." I believe we are about to have a gravitational explosion.

Before it is too late, let us review our calculations. Take a certain mass and distribute it in the physical space of a universe which has the shape of a three-dimensional spherical bubble within a four-dimensional cosmos. Then stipulate that the total mass-energy of the system, which is equal to the initial mass-energy plus the relativistic increase due to the speed of expansion, is also equal to its total negative gravitational energy. This is the same as stipulating that the total energy of the system is zero, and no simpler stipulation can be made. Write this down as an equation, for which we need only the initial mass, the gravitational constant, and the speed of light. Solve this equation and examine the solution you obtain.[1] This solution represents an explosion which proceeds with nearly the speed of light, with a continuously increasing mass but also a continuously decreasing density. And if you substitute the age of the universe today for the time appearing explicitly in this solution you obtain a density of the order of 10^{-30} gram per cc. This is the density of our present universe, within the margin of observational error. And if you like, make the initial mass from which you started, zero, and the solution is hardly affected. No known physical law has been violated in this calculation, but a yet unknown mechanism has been postulated for the trade of positive mass-energy for negative gravitational energy.

This is an intriguing result, which leads to the following picture.

Imagine a two-dimensional plane intersecting our three-dimensional universe within the four-dimensional cosmos I have assumed. This is similar to a plane intersecting a two-dimensional sphere within a three-dimensional space, and if this plane is the blackboard, we have a circle which expands. But we have chosen a plane which passes through the center of the earth, and here there is an increased curvature as we approach our tiny, enormously heavy mass. The experiment continues, the mass increases in weight, the curvature of space increases on both sides, and a critical point is reached when it wraps its own space around itself, shearing itself from its mother-universe, and beginning to expand on its own.

This picture may induce some final soul-searching questions, before fabricating the additional billion tons or so of our heavy particles, which will produce a gravitational crit in the center of our beloved planet.

[1] M. J. E. Golay, "On a connection between Mach's principle and the principle of relativity," *The Observatory*, vol. 79, no. 912, pp. 189–190.

Destruction of Universe Unlikely

Will this supreme experiment destroy our old universe while creating a new one? Probably not. Any annihilation of the universe would require its collapse, and anything resembling a return to the beginning implies an unlikely turnabout of the clock.

Will it create a local disturbance, of the order of a supernova, hardly felt in other solar systems of our galaxy, and barely observed from neighboring galaxies? Or will it produce only a cosmic seed which, wrapping its own space around itself, will make a clean break with the old universe, becoming a new and full-fledged three-dimensional universe of its own, within the four-dimensional cosmos containing all there is? A completely separate new universe, having no physical connection with the old, and producing its own stars and its own living and thinking creatures, who shall know of us no more than we shall know of them, like these ephemeral insects who never coexist with their parents and their offspring.

At this point I would like to ask you not to take too literally some of the things I am saying. I admit their fantasy makes them sound like science fiction literature. I could say nothing about the mechanism involved. In the absence of any physical experiment connecting electrical phenomena with gravitational phenomena, I could only assume the existence of such a mechanism based on the probably nonlinear character of the field equations which should eventually connect electrical and gravitational phenomena, while being careful not to violate known laws; a mechanism which may operate actively only for a few seconds, or even picoseconds, if indeed our concept of time is applicable to it. I have glossed over such serious difficulties as those which arise if we have the possibility of multiple creation, with several junior universes blowing up like smaller soap bubbles within the mother bubble, first interacting and then beginning to interfere with each other. I have not discussed what meaning can be attached to a world mass which consists almost entirely of the incremental relativistic mass of a vanishingly small initial mass. I have no good answer for several sound logical and even embarrassing questions about these and other points. I can only plead for a measure of license, when speculating about a nonrepugnant alternative to a philosophically repugnant once and for all universe, doomed to eventual decay, or to a physically untenable infinite universe stretching indefinitely backward and forward in time.

I said I would not talk about chromatography, and I think I have succeeded in that. I hope to have succeeded also in giving you an idea of the strange lands to which we may be led by communication philosophy, and by speculation about the clock-rewinding task which may challenge the intelligence of man.