Operations Research

May–June 1973

Science in the Systems Age: Beyond IE, OR, and MS*

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(Received November 16, 1972)

I BELIEVE we are leaving one cultural and technological age and entering another; that we are in the early stages of a change in our conception of the world, a change in our way of thinking about it, and a change in the technology with which we try to make it serve our purposes. These changes, I believe, are as fundamental and pervasive as were those associated with the Renaissance, the Age of the Machine that it introduced, and the Industrial Revolution that was its principal product. The socio-technical revolution we have entered may well come to be known as the *Resurrection.*

THE MACHINE AGE

THE INTELLECTUAL FOUNDATIONS of the Machine Age consist of two ideas about the nature of the world and a way of seeking understanding of it.

The first idea is called *reductionism.* It consists of the belief that everything in the world and every experience of it can be reduced, decomposed, or disassembled to ultimately simple elements, indivisible parts. These were taken to be atoms in physics; simple substances in chemistry; cells in biology; monads, directly observables, and basic instincts, drives, motives, and needs in psychology; and psychological individuals in sociology.

Reductionism gave rise to an *analytical* way of thinking about the world, a way of seeking explanations and, hence, of gaining understanding of it. For many, 'analysis' was synonymous with 'thought.' Analysis consists, first, of taking what is to be explained apart—disassembling it, if possible, down to the independent and indivisible parts of which it is composed; secondly, of explaining the behavior of these parts; and, finally, aggregating these partial explanations into an explanation of the whole. For example, the analysis of a problem consists of breaking it down into a set of as simple problems as possible, solving each, and assembling their solutions into a solution of the whole. If the analyst succeeds in decomposing the problem he faces into simpler problems that are independent of each other, aggregat-

* An invited address delivered at the Joint National Meeting of the OPERATIONS RESEARCH SOCIETY OF AMERICA, THE INSTITUTE OF MANAGEMENT SCIENCES, and the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, Atlantic City, New Jersey, November 9, 1972.

ing the partial solutions is not required, because the solution to the whole is the sum of the solutions to its independent parts.

It should be noted—even if with unjustified brevity—that the concepts 'division of labor' and 'organizational structure' are manifestations of analytical thinking.

In the Machine Age, understanding the world was taken to be the sum, or resultant, of understandings of its parts that were conceptualized as independently of each other as was possible. This, in turn, made it possible to divide the labor of seeking to understand the world into a number of virtually independent disciplines.

The second basic idea was that of *mechanism.* All phenomena were believed to be explainable by using only one ultimately simple relation, *cause-effect.* One thing or event was taken to be the cause of another, its effect, if it was both necessary and sufficient for the other.

Because a cause was taken to be sufficient for its effect, nothing was required to explain the effect other than the cause. Consequently, the quest for causes was environment-free. It employed what we now call 'closed-system' thinking. Laws—like that of freely falling bodies—were formulated so as to exclude environmental effects. Specially designed environments, called 'laboratories,' were used so as to exclude environmental effects on phenomena under study.

Environment-free causal laws permit no exceptions. Effects are completely determined by causes. Hence, the prevailing view of the world was *deterministic.* It was also *mechanistic,* because science found no need for teleological concepts—such as functions, goals, purposes, choice, and free will—in explaining any natural phenomenon; they were considered to be either unnecessary, illusory, or meaningless.

The commitment to causal thinking yielded a conception of the world as a machine; it was taken to be like a hermetically sealed clock—a self-contained mechanism whose behavior was completely determined by its own structure. The major question raised by this conception was: Is the world a self-winding clock, or does it require a winder? Most took the world to be a machine created by God to serve His purposes, a machine for doing God's work. Additionally, man was believed to have been created in God's image. Hence, it was quite natural for man to attempt to develop machines that would serve His purposes, that would do His work.

The conception of work that was used derived from the conception of the world as consisting ultimately of particles of matter with two intrinsic properties, mass and energy, and an extrinsic property, location in a space-time coordinate system. Work was taken to be the movement of mass through space or the application of energy to matter so as to transform either matter or energy, or matter into energy. Work that was to be mechanized was analyzed. Such analysis came to be called 'work study.' It was thus decomposed into work elements, indivisible tasks. To these, elementary machines—the wheel and axle, the inclined plane, and the lever—energized by other machines, were applied separately or in combination. Separate machines were developed to perform as many elementary tasks as possible. Men and machines, each performing one or a small number of elementary tasks repetitively, were organized into processing networks that became mass-production and assembly lines.

The Industrial Revolution brought about mechanization, the substitution of machines for man as a source of physical work. This process affected the nature of work left for men to do. They no longer did all the things necessary to make a product; they repeatedly performed a simple operation in the production process. Consequently, the more machines were used as a substitute for men at work, the more working men were made to behave like machines. The dehumanization of men's work was the irony of the Industrial Revolution.

THE SYSTEMS AGE

ALTHOUGH ERAS DO not have precise beginnings and ends, the 1940's can be said to have contained the beginning of the end of the Machine Age and the beginning of the Systems Age. This new age is the product of a new intellectual framework in which the doctrines of reductionism and mechanism and the analytical mode of thought are being supplemented by the doctrines of *expansionism*, *teleology*, and a new *synthetic* (or systems) mode of thought.

Expansionism is a doctrine maintaining that all objects and events, and all experiences of them, are parts of larger wholes. It does not deny that they have parts, but it focuses on the wholes of which they are part. It provides another way of viewing things, a way that is different from, but compatible with, reductionism. It turns attention from ultimate elements to a whole with interrelated parts, to *systems*. Preoccupation with systems emerged during the 1940's. Only a few of the highlights of this process are noted here.

In 1941 the American philosopher(ess) SUZANNE LANGER[2] argued that, over the preceding two decades, philosophy had shifted its attention from elementary particles, events, and their properties to a different kind of element, the *symbol*. A symbol is an element whose physical properties have essentially no importance. CHARLES W. MORRIS,[3] another American philosopher, built on Langer's work a framework for the scientific study of symbols and the *wholes* of which they were a part, *languages*. By so doing he expanded the center of attention. In 1949 CLAUDE SHANNON,[6] a mathematician at Bell Laboratories, developed a mathematical theory that turned attention to a still larger phenomenon, *communication*. Another famous mathematician at the Massachusetts Institute of Technology, NORBERT WIENER,[11] in his book *Cybernetics*, put communication into a still larger context, that of *control*. By the early 1950's, it became apparent that interest in control and communication were only aspects of an interest in a still larger phenomenon, *systems*, to which the biologist LUDWIG VON BERTALANFFY[10] drew attention with his work. 'Systems' has since been widely recognized as the new organizing concept of science. The concept is not new, but its organizing role in science is.

A system is a set of interrelated elements of any kind; for example, concepts (as in the number system), objects (as in a telephone system or human body), or people (as in a society). The set of elements has the following three properties.

1. The properties or behavior of each part of the set has an effect on the properties or behavior of the set as a whole. For example, every organ in an animal's body affects the performance of the body.

2. The properties and behavior of each part and the way they affect the whole depend on the properties and behavior of at least one other part in the set. Therefore, no part has an independent effect on the whole. For example, the effect that the heart has on the body depends on the behavior of the lungs.

3. Every possible subgroup of elements in the set has the first two properties. Each has an effect, and none can have an independent effect, on the whole. Therefore, the elements cannot be organized into independent subgroups. For example, all the subsystems in an animal's body—such as the nervous, respiratory, digestive, and motor subsystems—interact, and each affects the performance of the whole.

Because of these three properties, a set of elements that forms a system always has some characteristics, or can display some behavior, that none of its elements or subgroups can. Furthermore, membership in the set either increases or decreases the capabilities of each element, but it does not leave them unaffected. For example, parts of a living body cannot live apart from that body or a substitute. The power of a member of a group is always increased or decreased by such membership.

A system is more than the sum of its parts; it is an *indivisible whole*. It loses its essential properties when it is taken apart. The elements of a system may themselves be systems, and every system may be a part of a larger system.

Preoccupation with systems brings with it the *synthetic* mode of thought. In the analytic mode, it will be recalled, an explanation of the whole was derived from explanations of its parts. In synthetic thinking, something to be explained is viewed as part of a larger system and is explained in terms of its role in that larger system. For example, universities are explained by their role in the educational system, rather than by the behavior of their colleges and departments. The Systems Age is more interested in putting things together than in taking them apart.

Analytic thinking is, so to speak, outside-in thinking; synthetic thinking is inside-out. Neither negates the value of the other, but by synthetic thinking we can gain understanding that we cannot obtain through analysis, particularly of collective phenomena.

The synthetic mode of thought, when applied to systems problems, is called the *systems approach*. This way of thinking is based on the observation that, when each part of a system performs as well as possible, the system as a whole seldom performs as well as possible. This follows from the fact that the sum of the functioning of the parts is seldom equal to the functioning of the whole. This can be shown as follows.

Suppose we collect one each of every model of available automobile. Suppose further that we then ask some top-flight automotive engineers to determine which of these cars has the best carburetor. When they have done so, we note the result. Then we ask them to do the same for transmissions, fuel pumps, distributors, and so on through each part required to make an automobile. When this is completed, we ask them to remove the parts noted and assemble them into an automobile, each of whose parts is the best available. They will not be able to do so, because the parts will not fit together. Even if they could be assembled, in all likelihood they would not work well together. System performance depends critically on how the parts fit and work together, not merely on how well each performs independently.

Furthermore, a system's performance depends on how it relates to its environment, the larger system of which it is a part, and to other systems in that environment. For example, an automobile's performance depends on the weather, the road on which it is driven, and how well it and other cars are driven. Therefore, in systems thinking we try to evaluate the performance of a system by evaluating its functioning as a part of the larger system that contains it.

It will be recalled that in the Machine Age cause-effect was the central relation in terms of which all explanations were sought. At the turn of this century the distinguished American philosopher of science, E. A. SINGER, JR.,[7] noted that cause-effect was used in two different senses. First, it was used in the sense already discussed: a cause is a necessary and sufficient condition for its effect. Secondly, it was also used when one thing was taken as necessary but *not* sufficient for the other. He used as an example an acorn, which is necessary but insufficient for an oak; various soil and weather conditions are also necessary. Similarly, a mother—despite women's liberation—is only necessary, not sufficient, for her child. Singer chose to refer to this latter sense of cause-effect as *producer-product.* It can also be thought of as a probabilistic or nondeterministic cause-effect.

Singer[7] went on to show that studies of phenomena that use the producer-product relation were compatible with, but richer than, studies restricted to the use of deterministic causality. Furthermore, he showed that a theory of explanation based on producer-product permitted functional, goal-seeking, and purposeful behavior to be studied objectively and scientifically. These concepts no longer needed to be taken as meaningless or inappropriate for scientific study.

Later, biologist G. SOMMERHOFF[8] came independently to the same conclusions as Singer had. In the meantime, in a series of papers that laid the groundwork for cybernetics, ARTURO ROSENBLUETH, NORBERT WIENER, and J. H. BIGELOW[4,5] showed the great value of conceptualizing machines and man/machine systems as functioning, goal-seeking, and purposeful entities. In effect, they showed that, whereas it had been fruitful in the past to study men as though they were machines, it was now at least equally fruitful to study machines, man/machine systems, and, of course, men as though they were goal-seeking or purposeful. Thus, in the 1950's *teleology*—the study of goal-seeking and purposeful behavior—was brought into science and began to dominate our conceptualization of the world.

For example, in mechanistic thinking behavior is explained by identifying what caused it, never its effect. In teleological thinking, behavior can be explained either by what produced it or by what is is intended to produce. For example, a boy's going to the store can be explained either by the fact his mother sent him, or by the fact that he intends to buy ice cream for supper. Study of the functions, goals, and purposes of individuals and groups has yielded a greater ability to evaluate and improve their performance than mechanistically oriented research did.

THE POST-INDUSTRIAL REVOLUTION

THE DOCTRINES OF expansionism and teleology, and the synthetic mode of thought are both the producers and the products of the Post-Industrial Revolution. But this revolution is also the product of three technological developments, two of which occurred during the (First) Industrial Revolution. One of these emerged with the telegraph in the first half of the nineteenth century, followed by the invention of the telephone by Alexander Graham Bell in 1876, and of the wireless by Marconi in 1895. Radio and television followed in this century. Such devices mechanized communication, the transmission of symbols. Since symbols are not made of matter, their movement through space does not constitute physical work. The significance of this fact was not appreciated at the time of the invention of communication machines.

The second technology emerged with the development of devices that can observe and record the properties of objects and events. Such machines generate symbols that we call *data*. The thermometer, odometer, speedometer, and voltmeter are familiar examples of such instruments. In 1937 there was a major advance in the technology of observation when it 'went electronic' with the invention of radar and sonar.

Instruments can observe what we cannot observe without mechanical aids, or magnitudes and differences too large or small for our senses. Note that such instruments, like communication machines, do not perform physical work.

The third and key technology emerged in the 1940's with the development of the electronic digital computer. This machine could manipulate symbols logically. For this reason, it is frequently referred to as a thinking machine.

These three technologies made it possible to observe, communicate, and manipulate symbols. By organizing them into a system, it became possible to *mechanize mental work*, to *automate*. This is what the Post-Industrial Revolution is all about.

Development and utilization of automation technology requires an understanding of the mental processes that are involved in observing, recording, and processing data, communicating them, and using them to make decisions and control our affairs. Since 1940 a number of interdisciplines have been developed to generate and apply knowledge and understanding of mental processes. These include communication and information sciences, cybernetics, systems engineering, operations research, and the management and behavioral sciences. Such fields provide the software of the Post-Industrial Revolution.

THE ORGANIZING PROBLEMS OF THE SYSTEMS AGE

BECAUSE THE Systems Age is teleologically oriented, it is preoccupied with systems that are goal-seeking or purposeful; that is, systems that can display *choice* of either means or ends, or both. It is interested in purely mechanical systems only insofar as they can be used as instruments of purposeful systems. Furthermore, the Systems Age is most concerned with purposeful systems, some of whose parts are purposeful; these are called *social groups*. The most important class of social groups is the one containing systems whose parts perform different functions, that have a division of functional labor; these are called *organizations*. Systems-Age man is most interested in groups and organizations that are themselves parts of larger purposeful systems. All the groups and organizations, including institutions, that are part of society can be conceptualized as such three-level purposeful systems.

There are three ways in which such systems can be studied. We can try to increase the effectiveness with which they serve their own purposes, the *self-control* problem; the effectiveness with which they serve the purposes of their parts, the *humanization* problem; and the effectiveness with which they serve the purposes of the systems of which they are a part, the *environmentalization* problem. These are the three strongly interdependent organizing problems of the Systems Age.

SCIENCE IN THE SYSTEMS AGE

UP TO THIS point I have tried to deal with the question: What in the world is going on in the world? My response to this question provides a vantage point from which

I would now like to look at science in general and at the management sciences in particular.

Since its inception, science has not only been taking the world apart, but it has also been taking itself apart, although not without reason or benefit. The decomposition of science could not have been avoided. The reason is revealed in the statement with which Colin Cherry[1] opened his book, *On Human Communication*:

> Leibnitz, it has sometimes been said, was the last man to know everything. Though this is most certainly a gross exaggeration, it is an epigram with considerable point. For it it true that up to the last years of the eighteenth century our greatest mentors were able not only to compass the whole science of their day, perhaps with mastery of several languages, but to absorb a broad culture as well.

The continuous accumulation of scientific knowledge that occurred during and after the eighteenth century made it necessary to divide and classify this knowledge. Scientific disciplines were the product of this effort. Science formally separated itself from philosophy only a little more than a century ago. It then divided itself into physics and chemistry. Biology emerged out of chemistry, psychology out of biology, and the social sciences out of psychology. This much was completed at the beginning of this century. But scientific fission continued. Disciplines proliferated. The National Research Council now lists more than one hundred and fifty of them.

Disciplines are categories that facilitate filing the content of science. They are nothing more than filing categories. Nature is not organized the way our knowledge of it is. Furthermore, the body of scientific knowledge can, and has been, organized in different ways. No one way has ontological priority. The order in which the disciplines developed was dictated to a large extent by what society permitted scientists to investigate, not by any logical ordering of subject matter. Scientists started to investigate the areas that least challenged deeply held social, cultural, religious, and moral beliefs of the time. The subject matter of science was chosen—and not always successfully—so as to maximize the probability of survival of scientists and science. As science gained prestige, it pressed against the social barriers that obstructed its development; one by one they were breached.

But scientists and philosophers wanted to invest the history of science with more logic than history itself provided. Therefore, they sought to rationalize the order of disciplinary development by invoking the concept of a hierarchy of the sciences. They argued that physics deals with objects, events, and properties of both that were ultimately simple, hence irreducible and directly observable. Each successive discipline, it was argued, dealt with increasingly complex functions and aggregations of these objects, events, and properties. Hence, each discipline except physics was taken to rise out of, and to be reducible to, the one that preceded it. Physics was taken to be basic and fundamental. Dependence between sciences was taken to flow in only one direction.

This hierarchical myth is still widely accepted in and out of science. It is the basis of a caste system in the community of science that is as severe and irrational as any that has existed in society.

It is still widely believed that the physical sciences alone deal with ultimate reality and that they have no need of the other disciplines in their effort to do so. This belief is maintained despite the fact that we can demonstrate that no concept used in any one discipline is ultimately fundamental and incapable of being illuminated by work in other disciplines.

Consider, for example, a concept used in physics that, perhaps more than any other, is thought to be its exclusive property: *time*. Physicists have dealt with time in one of two ways. They have either taken it to be a primitive concept that cannot be defined, and hence a concept whose meaning can only be grasped by direct experience of it; or they have dealt with it operationally, defining it by the operations used to measure it. Techniques of measuring time in physics all derive from use of the rotation of the earth around the sun as a basic unit. Clocks, sun dials, water clocks, sand clocks, and so on are instruments to divide this unit into equal parts. Thus, in physics time is dealt with as an ateleological astronomical concept. It is generally assumed that contributions to understanding it cannot be made by any other discipline.

This is not the case. Time can be considered teleologically, not as a property of the universe that is out there for us to take, but as a concept deliberately constructed by man to serve his purposes.

People develop alternative ways of individuating events. For example, a person may differentiate between breakfasts by their content, location, or by those with whom he had the meal. Some of these individuating properties may be adequate only in special circumstances. He may have the same breakfast with the same people at the same place on different days. Two events that occur to the same individual may be the same with respect to every property except one, time. Two events that occur to the same individual at the same time cannot be otherwise identical: they must differ in some respect; otherwise, they would not be two events.

Therefore, from a functional point of view, time is a property of events that is sufficient to enable a person to individuate any two changes in the same property of the same thing. Because we measure time using physical phenomena, we erroneously conclude it is a physical concept. The error becomes apparent in situations in which astronomical measures do not serve our purposes well. In measuring the rate of growth of plants, for example, C. W. THORNTHWAITE[9] found astronomical time inadequate. He sought a biological clock and found one in the pea plant; he used the time between appearances of successive nodes on the pea plant as units of time for his work. These units were of different duration when measured astronomically, but they made possible more accurate prediction and control of harvests than did hours and days. We measure time by using events that are identical in all respects save time; and, in principle, these can be of any type—which type we use is determined by our purposes.

As the application of science increased it became useful to organize its findings functionally around areas of application, into professions, as well as into disciplines. Old professions that preceded science borrowed from a number of scientific disciplines and new ones did so as well.

The disciplinary and professional classifications of scientific knowledge are orthogonal to one another, and hence can be represented by a matrix in which the disciplines form the rows and the professions the columns. New rows and columns can be expected to be added in the future.

As the problems to which science was addressed became more complex—and particularly as it began to address itself to problem complexes, systems of problems that I like to call *messes*—a new organization of scientific and technological effort was required. The first response to this need occurred between the two World Wars and took the form of *multidisciplinary* research. In such research the problem complex investigated was decomposed into unidisciplinary and uniprofessional problems that were taken to be solvable independently of each other. Hence, they were assigned to different disciplines or professions, separately solved, and the solutions were either aggregated or allowed to aggregate themselves. With the emergence of systems thinking, however, it was realized that the effect of multidisciplinary research on the treatment of the whole was frequently far from the best that could be obtained.

This realization gave rise to *interdisciplinary* research, in which the problem complex was not disassembled into disciplinary parts, but was treated as a whole by representatives of different disciplines working collaboratively. Operations research and the management sciences were among the interdisciplines born of this effort. So were cybernetics, the organizational sciences, the policy sciences, planning science, general systems research, and the communication sciences, among others.

Universities began to educate the young for such work. Those so educated were not of any one discipline but of the intersection of several. Hence, their loyalty was not directed to one discipline but to an interdisciplinary concept. But this did not last long. The interdisciplines sought recognition and status by emulating the disciplines and professions. Academic departments and professional societies were formed along conventional lines. The interdisciplines began to identify themselves with the instruments that they developed and used—that is structurally—rather than with what these instruments were used for—that is, functionally. They began to introvert, to look inward and contemplate their own methods and accomplishments, rather than the messes that had given rise to their activities. Jurisdictional disputes and efforts to individuate interdisciplines arose between activities created to eliminate just such disputes and individuation.

As the problem complexes with which we concern ourselves increase in complexity, the need for bringing the interdisciplines together increases. What we need may be called *metadisciplines*, and what they are needed for may be called *systemology*.

The formation of interdisciplines in the last three decades can now be understood as a transitional development, a beginning to an evolutionary synthesis of human knowledge, not only within science, but between science and technology, and, most importantly, between science and the humanities. Consider the distinction between science and the humanities. I believe that in the Systems Age science will come to be understood as the search for similarities among things that are apparently different; and the humanities will come to be understood as the search for differences among things that are apparently the same. The former seeks generality; the latter uniqueness. This makes science and the humanities like the head and tail of a coin; they can be looked at and discussed separately, but they cannot be separated. Consider why.

In the conduct of any inquiry, we must determine the ways in which the subject under study is similar to other subjects previously studied. Doing so enables us to bring to bear what we have already learned. But, in addition, it is also necessary to determine how the subject at hand differs from any we have previously studied: in what ways it is unique. Its uniqueness defines what we have yet to learn before we can solve the problems it presents. Thus, the humanities define the aspects of messes that we still have to learn how to handle, and science provides ways both of handling or researching the aspects that have previously been dealt with, and of finding ways of approaching the aspects that have not been studied previously.

The effective study of large-scale social systems requires the synthesis of science and the humanities, of science and technology, and of the disciplines within science and the professions that use them.

Despite the need for integration, universities and professional and scientific societies preserve the autonomy of the parts of science and their application. What is needed is not a temporary association of autonomous interdisciplines such as we have here at Atlantic City, but a permanent integration of interdisciplines that yields a broader synthesis of methods and knowledge than any yet attained.

We need a fusion of interdisciplines that extends well beyond those represented here. Nevertheless, a fusion of these three would be a significant step in the right direction. But as far as I can tell—after considerable effort to merge two of them—they would rather die separately than live together. And they are dying despite their growth. Death is *not* a function of the number of cells in a body, but of their vitality: the membership of even a cemetery can expand continuously.

None of what I have said denies the usefulness of either disciplinary science or the professions. They will remain useful in dealing with problem areas that can be decomposed into problems that are independent of each other. But the major organizational and social messes of our time do not lend themselves to such decomposition. They must be attacked holistically, with a comprehensive systems approach.

Nor are my remarks intended to diminish the past accomplishments of IE, MS, and OR—they have been significant and I share with you a pride in them. But their accomplishments are becoming less significant because their development has not kept pace with the growing complexity of the situations with which managers and administrators are faced.

As currently conceived, taught, and organized, industrial engineering is not broad enough to engineer industry effectively by itself. This is obvious. Look at the wide variety of other types of engineers crawling all over industry. The management sciences are not broad enough to make management scientific. What percentage of the decisions of even the managers most dedicated to these sciences are based on science? Operations research is not broad enough to research effectively the operating characteristics of our social system that most urgently need research: discrimination, inequality within and between nations, the bankruptcy of education, the inefficiency of health services, increasing criminality, deterioration of the environment, war, and so on. This is not to say that IE, MS, and OR are no good, but it does say that they are *not good enough*. Each of them suffers not only from the lack of competencies that are required to deal with the messes that preoccupy those who manage most public and private systems, but also because they use Machine-Age concepts and methods in attempts to deal with Systems-Age problems.

Meetings such as this one should be dedicated to the marriage of movements, and to the conception and birth of ways of coping with complexity. But, instead, they are wakes at which interdisciplines are laid out and put on display in their best attire. Eulogies are delivered in which accounts are given about how messes were murdered by reducing them to problems, how problems were murdered by reducing them to models, and how models were murdered by excessive exposure to the elements of mathematics.

But those who attend a wake are not dead. They can still raise hell. And, if they do, even a corpse—like that of James Joyce's Finnegan—may respond and rise with a shout.

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