Classical papers section

Science and complexity

Warren Weaver

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It is easy to get caught up in the excitement surrounding the study of complexity and how our new learning might be applied to the problems we face today. We often feel like pioneers in a new land, making new discoveries. For those involved in charting such a course, it is easy to lose historical perspective and the path already taken by others. It is to these earlier pioneers that the Classical Papers Section is dedicated. Such a side trip to the archives can quickly bring the reader a dose of reality, that some "new" ideas are really only "rediscovered." Similarly, our view of the future can gain some perspective when reading about earlier predictions of the future, what we now call the present.

Reaching back almost 60 years, *E:CO* readers are invited to read a classic article by Warren Weaver (1894-1978). For historical setting, this article was published shortly after World War II and is influenced by operations research and the first computers developed for the war effort. During the war, Weaver headed the Applied Mathematics Panel (AAAS, 2004), a position that led to familiarity with many of the top scientists of the era. It was a time of great advances in science and optimism for more growth in the future. This article was also written at the time Weaver was formulating ideas that would later be published with Claude Shannon in *The mathematical theory of communication*, which laid the foundation for information theory. Weaver's thoughts during this time on how computers might be employed in machine translation were later collected in his famous memorandum on the topic that "formulated goals and methods before most people had any idea of what computers might be capable of" (Griffin,1997).

The optimistic attitude of the power of science is also reflected in "Science and Complexity." In the first part of the article, Weaver offers a historical perspective of problems addressed by science, a classification that separates simple, few-variable problems from the "disorganized complexity" of numerous-variable problems suitable for probability analysis. The problems in the middle are "organized complexity" with a moderate number of variables and interrelationships that cannot be fully captured in probability statistics nor sufficiently reduced to a simple formula.

The second part of the article addresses how the study of organized complexity might be approached. The answer is through harnessing the power of computers and cross-discipline collaboration. Weaver predicts:

"*Some scientists will seek and develop for themselves new kinds of collaborative arrangements; that these groups will have members drawn from essentially all fields of science; and that these new ways of working, effectively instrumented by huge computers, will contribute greatly to the advance which the next half century will surely achieve in handling the complex, but essentially organic, problems of the biological and social sciences.*" (Weaver, 1948)

When reading this, there is a bit of *déjà vu* in what we sometimes hear today of our study of complexity. So too in the statement that "science has, to date, succeeded in solving a bewildering number of relatively easy problems, whereas the hard problems, and the ones which perhaps promise most for man's future, lie ahead" (Weaver, 1948). In the end the reader is left with conflicting feelings of surprise that we are not further along in our understanding of complexity given Weaver's ideas nearly 60 years ago, while also still being optimistic in our success for the same reasons Weaver was optimistic.

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SCIENCE AND COMPLEXITY

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SCIENCE has led to a multitude of results that affect men's lives. Some of these results are embodied in mere conveniences of a relatively trivial sort. Many of them, based on science and developed through technology, are essential to the machinery of modern life. Many other results, especially those associated with the biological and medical sciences, are of unquestioned benefit and comfort. Certain aspects of science have profoundly influenced men's ideas and even their ideals. Still other aspects of science are thoroughly awesome.

How can we get a view of the function that science should have in the developing future of man? How can we appreciate what science really is and, equally important, what science is not? It is, of course, possible to discuss the nature of science in general philosophical terms. For some purposes such a discussion is important and necessary, but for the present a more direct approach is desirable. Let us, as a very realistic politician used to say, let us look at the record. Neglecting the older history of science, we shall go back only three and a half centuries and take a broad view that tries to see the main features, and omits minor details. Let us begin with the physical sciences, rather than the biological, for the place of the life sciences in the descriptive scheme will gradually become evident.

Problems of Simplicity

Speaking roughly, it may be said that the seventeenth, eighteenth, and nineteenth centuries formed the period in which physical science learned variables, which brought us the telephone and the radio, the automobile and the airplane, the phonograph and the moving pictures, the turbine and the Diesel engine, and the modern hydroelectric power plant.

The concurrent progress in biology and medicine was also impressive, but that was of a different character. The significant problems of living organisms are seldom those in which one can rigidly maintain constant all but two variables. Living things are more likely to present situations in which a half-dozen, or even several dozen quantities are all varying simultaneously, and in subtly interconnected ways. Often they present situations in which the essentially important quantities are either non-quantitative, or have at any rate eluded identification or measurement up to the moment. Thus biological and medical problems often involve the consideration of a most complexly organized whole. It is not surprising that up to 1900 the life sciences were largely concerned with the necessary preliminary stages in the application of the scientific method—preliminary stages which chiefly involve collection, description, classification, and the observation of concurrent and apparently correlated

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effects. They had only made the brave beginnings of quantitative theories, and hardly even begun detailed explanations of the physical and chemical mechanisms underlying or making up biological events.

To sum up, physical science before 1900 was largely concerned with two-variable *problems of simplicity;* whereas the life sciences, in which these problems of simplicity are not so often significant, had not yet become highly quantitative or analytical in character.

Problems of Disorganized Complexity

Subsequent to 1900 and actually earlier, if one includes heroic pioneers such as Josiah Willard Gibbs, the physical sciences developed an attack on nature of an essentially and dramatically new kind. Rather than study problems which involved two variables or at most three or four, some imaginative minds went to the other extreme, and said: "Let us develop analytical methods which can deal with two billion variables." That is to say, the physical scientists, with the mathematicians often in the vanguard, developed powerful techniques of probability theory and of statistical mechanics to deal with what may be called problems of *disorganized complexity.*

This last phrase calls for explanation. Consider first a simple illustration in order to get the flavor of the idea. The classical dynamics of the nineteenth century was well suited for analyzing and predicting the motion of a single ivory ball as it moves about on a billiard table. In fact, the relationship between positions of the ball and the times at which it reaches these positions forms a typical nineteenth-century problem of simplicity. One can, but with a surprising increase in difficulty, analyze the motion of two or even of three balls on a billiard table. There has been, in fact, considerable study of the mechanics of the standard game of billiards. But, as soon as one tries to analyze the motion of ten or fifteen balls on the table at once, as in pool, the problem becomes unmanageable, not because there is any theoretical difficulty, but just because the actual labor of dealing in specific detail with so many variables turns out to be impracticable.

Imagine, however, a large billiard table with millions of balls rolling over its surface, colliding with one another and with the side rails. The great surprise is that the problem now becomes easier, for the methods of statistical mechanics are applicable. To be sure the detailed history of one special ball can not be traced, but certain important questions can be answered with useful precision, such as: On the average how many balls per second hit a given stretch of rail? On the average how far does a ball move before it is hit by some other ball? On the average how many impacts per second does a ball experience?

Earlier it was stated that the new statistical methods were applicable to problems of disorganized complexity. How does the word "disorganized" apply to the large billiard table with the many balls? It applies because the methods of statistical mechanics are valid only when the balls are distributed, in their positions and motions, in a helter-skelter, that is to say a disorganized, way. For example, the statistical methods would not apply if someone were to arrange the balls in a row parallel to one side rail of the table, and then start them all moving in precisely parallel paths perpendicular to the row in which they stand. Then the balls would never collide with each other nor with two of the rails, and one would not have a situation of disorganized complexity.

From this illustration it is clear what is meant by a problem of disorganized complexity. It is a problem in which the number of variables is very large, and one in which each of the many variables has a behavior which is individually erratic, or perhaps totally unknown. However, in spite of this helter-skelter, or unknown, behavior of all the individual variables, the system as a whole possesses certain orderly and analyzable average properties.

A wide range of experience comes under the label of disorganized complexity. The method applies with increasing precision when the number of variables increases. It applies with entirely useful precision to the experience of a large telephone exchange, in predicting the average frequency of calls, the probability of overlapping calls of the same number, etc. It makes possible the financial stability of a life insurance company. Although the company can have no knowledge whatsoever concerning the approaching death of any one individual, it has dependable knowledge of the average frequency with which deaths will occur.

This last point is interesting and important. Statistical techniques are not restricted to situations where the scientific theory of the individual events is very well known, as in the billiard example where there is a beautifully precise theory for the impact of one ball on another. This technique can also be applied to situations, like the insurance example, where the individual event is as shrouded in mystery as is the chain of complicated and unpredictable events associated with the accidental death of a healthy man.

The examples of the telephone and insurance companies suggests a whole array of practical applications of statistical techniques based on disorganized complexity. In a sense they are unfortunate examples, for they tend to draw attention away from the more fundamental use which science makes of these new techniques. The motions of the atoms which form all matter, as well as the motions of the stars which form the universe, come under the range of these new techniques. The fundamental laws of heredity are analyzed by them. The laws of thermodynamics, which describe basic and inevitable tendencies of all physical systems, are derived from statistical considerations. The entire structure of modern physics, our present concept of the nature of the physical universe, and of the accessible experimental facts concerning it rest on these statistical concepts. Indeed, the whole question of evidence and the way in which knowledge can be inferred from evidence are now recognized to depend on these same statistical ideas, so that probability notions are essential to any theory of knowledge itself.

Problems of Organized Complexity

This new method of dealing with disorganized complexity, so powerful an advance over the earlier two-variable methods, leaves a great field untouched. One is tempted to oversimplify, and say that scientific methodology went from one extreme to the other—from two variables to an astronomical number—and left untouched a great middle region. The importance of this middle region, moreover, does not depend primarily on the fact that the number of variables involved is moderate—large compared to two, but small compared to the number of atoms in a pinch of salt. The problems in this middle region, in fact, will often involve a considerable number of variables. The really important characteristic of the problems of this middle region, which science has as yet little explored or conquered, lies in the fact that these problems, as contrasted with the disorganized situations with which statistics can cope, show the essential feature of *organization*. In fact, one can refer to this group of problems as those of *organized complexity*.

What makes an evening primrose open when it does? Why does salt water fail to satisfy thirst? Why can one particular genetic strain of microorganism synthesize within its minute body certain organic compounds that another strain of the same organism cannot manufacture? Why is one chemical substance a poison when another, whose molecules have just the same atoms but assembled into a mirror-image pattern, is completely harmless? Why does the amount of manganese in the diet affect the maternal instinct of an animal? What is the description of aging in biochemical terms? What meaning is to be assigned to the question: Is a virus a living organism? What is a gene, and how does the original genetic constitution of a living organism express itself in the developed characteristics of the adult? Do complex protein molecules "know how" to reduplicate their pattern, and is this an essential clue to the problem of reproduction of living creatures? All these are certainly complex problems, but they are not problems of disorganized complexity, to which statistical methods hold the key. They are all problems which involve dealing simultaneously with a *sizable number of factors which are interrelated into an organic whole*. They are all, in the language here proposed, problems of *organized complexity*.

On what does the price of wheat depend? This too is a problem of organized complexity. A very substantial number of relevant variables is involved here, and they are all interrelated in a complicated, but nevertheless not in helter-skelter, fashion.

How can currency be wisely and effectively stabilized? To what extent is it safe to depend on the free interplay of such economic forces as supply and demand? To what extent must systems of economic control be employed to prevent the wide swings from prosperity to depression? These are also obviously complex problems, and they too involve analyzing systems which are organic wholes, with their parts in close interrelation.

How can one explain the behavior pattern of an organized group of persons such as a labor union, or a group of manufacturers, or a racial minority? There are clearly many factors involved here, but it is equally obvious that here also something more is needed than the mathematics of averages. With a given total of national resources that can be brought to bear, what tactics and strategy will most promptly win a war, or better: what sacrifices of present selfish interest will most effectively contribute to a stable, decent, and peaceful world?

These problems—and a wide range of similar problems in the biological, medical, psychological, economic, and political sciences—are just too complicated to yield to the old nineteenth-century techniques which were so dramatically successful on two-, three-, or four-variable problems of simplicity. These new problems, moreover, cannot be handled with the statistical techniques so effective in describing average behavior in problems of disorganized complexity.

These new problems, and the future of the world depends on many of them, requires science to make a third great advance, an advance that must be even greater than the nineteenth-century conquest of problems of simplicity or the twentieth-century victory over problems of disorganized complexity. Science must, over the next 50 years, learn to deal with these problems of organized complexity.

Is there any promise on the horizon that this new advance can really be accomplished? There is much general evidence, and there are two recent instances of especially promising evidence. The general evidence consists in the fact that, in the minds of hundreds of scholars all over the world, important, though necessarily minor, progress is already being made on such problems. As never before, the quantitative experimental methods and the mathematical analytical methods of the physical sciences are being applied to the biological, the medical, and even the social sciences. The results are as yet scattered, but they are highly promising. A good illustration from the life sciences can be seen by a comparison of the present situation in cancer research with what it was twenty-five years ago. It is doubtless true that we are only scratching the surface of the cancer problem, but at least there are now some tools to dig with and there have been located some spots beneath which almost surely there is pay-dirt. We know that certain types of cancer can be induced by certain pure chemicals. Something is known of the inheritance of susceptibility to certain types of cancer. Million-volt rays are available, and the even more intense radiations made possible by atomic physics. There are radioactive isotopes, both for basic studies and for treatment. Scientists are tackling the almost incredibly complicated story of the biochemistry of the aging organism. A base of knowledge concerning the normal cell is being established that makes it possible to recognize and analyze the pathological cell. However distant the goal, we are now at last on the road to a successful solution of this great problem.

In addition to the general growing evidence that problems of organized complexity can be successfully treated, there are at least two promising bits of special evidence. Out of the wickedness of war have come two new developments that may well be of major importance in helping science to solve these complex twentieth-century problems.

The first piece of evidence is the wartime development of new types of electronic computing devices. These devices are, in flexibility and capacity, more like a human brain than like the traditional mechanical computing device of the past. They have "memories" in which vast amounts of information can be stored. They can be "told" to carry out computations of very intricate complexity, and can be left unattended while they go forward automatically with their task. The astounding speed with which they proceed is illustrated by the fact that one small part of such a machine, if set to multiplying two ten-digit numbers, can perform such multiplications some 40,000 times faster than a human operator can say "Jack Robinson." This combination of flexibility, capacity, and speed makes it seem likely that such devices will have a tremendous impact on science. They will make it possible to deal with problems which previously were too complicated, and, more importantly, they will justify and inspire the development of new methods of analysis applicable to these new problems of organized complexity.

The second of the wartime advances is the "mixed-team" approach of operations analysis. These terms require explanation, although they are very familiar to those who were concerned with the application of mathematical methods to military affairs.

As an illustration, consider the over-all problem of convoying troops and supplies across the Atlantic. Take into account the number and effectiveness of the naval vessels available, the character of submarine attacks, and a multitude of other factors, including such an imponderable as the dependability of visual watch when men are tired, sick, or bored. Considering a whole mass of factors, some measurable and some elusive, what procedure would lead to the best over-all plan, that is, best from the combined point of view of speed, safety, cost, and so on? Should the convoys be large or small, fast or slow? Should they zigzag and expose themselves longer to possible attack, or dash in a speedy straight line? How are they to be organized, what defenses are best, and what organization and instruments should be used for watch and attack?

The attempt to answer such broad problems of tactics, or even broader problems of strategy, was the job during the war of certain groups known as the operations analysis groups. Inaugurated with brilliance by the British, the procedure was taken over by this country, and applied with special success in the Navy's anti-submarine campaign and in the Army Air Forces. These operations analysis groups were, moreover, what may be called mixed teams. Although mathematicians, physicists, and engineers were essential, the best of the groups also contained physiologists, biochemists, psychologists, and a variety of representatives of other fields of the biochemical and social sciences. Among the outstanding members of English mixed teams, for example, were an endocrinologist and an X-ray crystallographer. Under the pressure of war, these mixed teams pooled their resources and focused all their different insights on the common problems. It was found, in spite of the modern tendencies toward intense scientific specialization, that members of such diverse groups could work together and could form a unit which was much greater than the mere sum of its parts. It was shown that these groups could tackle certain problems of organized complexity, and get useful answers.

It is tempting to forecast that the great advances that science can and must achieve in the next fifty years will be largely contributed to by voluntary mixed teams, somewhat similar to the operations analysis groups of war days, their activities made effective by the use of large, flexible, and highspeed computing machines. However, it cannot be assumed that this will be the exclusive pattern for future scientific work, for the atmosphere of complete intellectual freedom is essential to science. There will always, and properly, remain those scientists for whom intellectual freedom is necessarily a private affair. Such men must, and should, work alone. Certain deep and imaginative achievements are probably won only in such a way. Variety is, moreover, a proud characteristic of the American way of doing things. Competition between all sorts of methods is good. So there is no intention here to picture a future in which all scientists are organized into set patterns of activity. Not at all. It is merely suggested that some scientists will seek and develop for themselves new kinds of collaborative arrangements; that these groups will have members drawn from essentially all fields of science; and that these new ways of working, effectively instrumented by huge computers, will contribute greatly to the advance which the next half century will surely achieve in handling the complex, but essentially organic, problems of the biological and social sciences.

The Boundaries of Science

Let us return now to our original questions. What is science? What is not science? What may be expected from science?

Science clearly is a way of solving problems—not all problems, but a large class of important and practical ones. The problems with which science can deal are those in which the predominant factors are subject to the basic laws of logic, and are for the most part measurable. Science is a way of organizing reproducible knowledge about such problems; of focusing and disciplining imagination; of weighing evidence; of deciding what is relevant and what is not; of impartially testing hypotheses; of ruthlessly discarding data that prove to be inaccurate or inadequate; of finding, interpreting, and facing facts, and of making the facts of nature the servants of man.

The essence of science is not to be found in its outward appearance, in its physical manifestations; it is to be found in its inner spirit. That austere but exciting technique of inquiry known as the scientific method is what is important about science. This scientific method requires of its practitioners high standards of personal honesty, open-mindedness, focused vision, and love of the truth. These are solid virtues, but science has no exclusive lien on them. The poet has these virtues also, and often turns them to higher uses.

Science has made notable progress in its great task of solving logical and quantitative problems. Indeed, the successes have been so numerous and striking, and the failures have been so seldom publicized, that the average man has inevitably come to believe that science is just about the most spectacularly successful enterprise man ever launched. The fact is, of course, that this conclusion is largely justified.

Impressive as the progress has been, science has by no means worked itself out of a job. It is soberly true that science has, to date, succeeded in solving a bewildering number of relatively easy problems, whereas the hard problems, and the ones which perhaps promise most for man's future, lie ahead.

We must, therefore, stop thinking of science in terms of its spectacular successes in solving problems of simplicity. This means, among other things, that we must stop thinking of science in terms of gadgetry. Above all, science must not be thought of as a modern improved black magic capable of accomplishing anything and everything.

Every informed scientist, I think, is confident that science is capable of tremendous further contributions to human welfare. It can continue to go forward in its triumphant march against physical nature, learning new laws, acquiring new power of forecast and control, making new material things for man to use and enjoy. Science can also make further brilliant contributions to our understanding of animate nature, giving men new health and vigor, longer and more effective lives, and a wiser understanding of human behavior. Indeed, I think most informed scientists go even further and expect that the precise, objective, and analytical techniques of science will find useful application in limited areas of the social and political disciplines.

There are even broader claims which can be made for science and the scientific method. As an essential part of his characteristic procedure, the scientist insists on precise definition of terms and clear characterization of his problem. It is easier, of course, to define terms accurately in scientific fields than in many other areas. It remains true, however, that science is an almost overwhelming illustration of the effectiveness of a well-defined and accepted language, a common set of ideas, a common tradition. The way in which this universality has succeeded in cutting across barriers of time and space, across political and cultural boundaries, is highly significant. Perhaps better than in any other intellectual enterprise of man, science has solved the problem of communicating ideas, and has demonstrated the world-wide cooperation and community of interest which then inevitably results.

Yes, science is a powerful tool, and it has an impressive record. But the humble and wise scientist does not expect or hope that science can do everything. He remembers that science teaches respect for special competence, and he does not believe that every social, economic, or political emergency would be automatically dissolved if "the scientists" were only put into control. He does not—with a few aberrant exceptions—expect science to furnish a code of morals, or a basis for esthetics. He does not expect science to furnish the yardstick for measuring, nor the motor for controlling, man's love of beauty and truth, his sense of value, or his convictions of faith. There are rich and essential parts of human life which are alogical, which are immaterial and non-quantitative in character, and which cannot be seen under the microscope, weighed with the balance, nor caught by the most sensitive microphone.

If science deals with quantitative problems of a purely logical character, if science has no recognition of or concern for value or purpose, how can modern scientific man achieve a balanced good life, in which logic is the companion of beauty, and efficiency is the partner of virtue?

In one sense the answer is very simple: our morals must catch up with our machinery. To state the necessity, however, is not to achieve it. The great gap, which lies so forebodingly between our power and our capacity to use power wisely, can only be bridged by a vast combination of efforts. Knowledge of individual and group behavior must be improved. Communication must be improved between peoples of different languages and cultures, as well as between all the varied interests which use the same language, but often with such dangerously differing connotations. A revolutionary advance must be made in our understanding of economic and political factors. Willingness to sacrifice selfish short-term interests, either personal or national, in order to bring about long-term improvement for all must be developed.

None of these advances can be won unless men understand what science really is; all progress must be accomplished in a world in which modern science is an inescapable, ever-expanding influence.