Pergamon

Environmental Toxicology and Chemistry, Vol. 13, No. 12, pp. 1881-1885, 1994

Printed in the USA
0730-7268/94 $6.00 + .00

0730-7268(94)00143-X

Annual Review

UNCERTAINTY, COMPLEXITY AND POST-NORMAL SCIENCE

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(*Received* 26 *May* 1993; *Accepted* 13 *May* 1994)

Abstract — The quality of the scientific inputs to the policy process is known to be problematic. No one can claim "truth" for his results. Nor can uncertainty be banished, but good quality can be achieved by its proper management. The interaction of systems uncertainties and decision stakes can be used to provide guidance for the choice of appropriate problem-solving strategies. When either or both of these are high, then mission-oriented *applied science* and client-serving *professional consultancy* are not adequate in themselves, and an issue-driven *post-normal science* is necessary. Just as in cases with ethical complexities (as in biomedical science) there must be an "extended peer community," including all stakeholders in the dialogue, for evaluating quality of scientific information for the policy process.

Keywords — Uncertainty Quality Complexity Post-normal science

INTRODUCTION

Science evolves, responding to its leading challenges as they change through history. The problems of global environmental risk, along with those of equity among peoples, present perhaps the greatest collective task now facing humanity. In response, new scientific approaches for problem solving for global environmental issues are already being developed. Traditional oppositions, as between disciplines within natural science, and between the "hard" and the "soft" sciences, are being overcome. The reductionist, analytical worldview that divides systems into ever smaller elements, studied by ever more esoteric specialties, is being replaced by a systemic, synthetic, and humanistic approach. Natural systems are recognized as complex and dynamic; this entails moving to a science based on unpredictability, incomplete control, and a plurality of legitimate perspectives.

We are now witnessing a growing awareness among all those concerned with global issues that no single cultural tradition, no matter how successful in the past, can supply all the answers for the problems of the planet. Closely connected with the emergence of these changed attitudes is a new methodology that reflects and helps to guide the development of a new scientific approach to problem solving for global environmental issues. In this, uncertainty is not banished but is managed, and values are not presupposed but are made explicit. The model for scientific argument is changing from a formalized deduction to an interactive dialogue. The paradigmatic science is no longer one whose explanations are unrelated to space, time, and process; the historical dimension, including human reflection on past and future change, is now becoming an integral part of a scientific characterization of nature and our place in it.

In this article we focus on two aspects of the emergent problem-solving strategy. One is the quality of scientific information analysed in terms of both the different sorts of uncertainty in knowledge and the intended functions of the information [1]. The other aspect refers to problem-solving strategies analysed in terms of uncertainties in both knowledge and ethics. When science is applied to policy issues, it cannot provide certainty in policy recommendations, and the conflicting values in any decision process cannot be ignored even in the problem-solving work itself.

For the analysis, we make use of these two crucial aspects of science in the policy domain: uncertainty and value conflict. We distinguish among three problem-solving strategies that are appropriate in different circumstances. For this, we employ two concepts,"systems uncertainties" and "decision stakes" (which we shall define later); they refer, respectively, to what is not fully known in the specification of the scientific problem, and to the commitments of the various stakeholders in the policy issue. These provide the two dimensions for a graphic display of three problem-solving strategies, from the most narrowly defined to the most comprehensive. Two of the strategies, *applied science* and *professional consultancy*, are familiar from past experience with scientific or professional practice. The third, referred to here as *post-normal science*, is appropriate where systems uncertainties or decision stakes (or both) are high. It is particularly useful in the practice of the research dealing with global environmental issues [2]. Here the problems of quality assurance of scientific information are particularly acute and require new conceptions of scientific methodology.

In this new approach to scientific decision making, the evaluation of scientific inputs requires an "extended peer community" [3,4]. This extension of legitimacy to new participants in policy dialogues has important implications for

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Presented at the Symposium on New Approaches in Risk Assessment and Uncertainty Analysis, 13th Annual Meeting, Society of Environmental Toxicology and Chemistry, Cincinnati, Ohio, November 8-12, 1992.

society and for science as well. With mutual respect among various perspectives and forms of knowing, there is a possibility for the development of a genuine and effective democratic element in the life of science. The challenges of global environmental issues can then become the successors of the earlier great "conquests," as of disease and then of space, in providing symbolic meaning and a renewed sense of adventure for a new generation of recruits to science in the future.

PROBLEM-SOLVING STRATEGIES

To characterize a problem involving global environmental issues, we can think of it as one where facts are uncertain, values are in dispute, stakes are high, and decisions urgent. In such cases, a simple, linear methodology based on the example of a "pure" science of laboratory research will not be likely to provide much guidance for solving the complex issues involved in such problems. However, emerging environmental problems do not render the use of traditional scientific approaches irrelevant; the task is to choose the appropriate kind of scientific problem-solving strategy for each particular issue. This is why we have a detailed discussion of applied science and professional consultancy along with post-normal science.

This conceptual approach to problem solving is presented in a diagram with three distinctive features. First (and this is an innovation for scientific methodology), it shows the interaction of the epistemic (knowledge) and axiological (values) aspects of scientific problems. These are depicted as the axes of a diagram, representing the intensity of uncertainty and of decision stakes, respectively. As shown in Figure 1, systems uncertainties and decision stakes are the opposites of attributes that had traditionally been thought to characterize science, namely its certainty and its value neutrality. (This is the second innovative feature of our analysis.) Finally, the two dimensions are themselves displayed as each comprising three discrete intervals. In this way, the diagram is constructed to have three zones representing and characterizing three kinds of problem-solving strategies (Fig. 1). We will discuss these below.

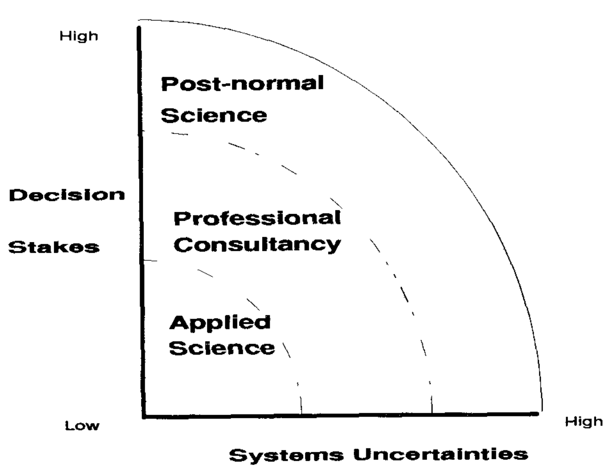

Fig. 1. Three types of problem-solving strategy.

The term "systems uncertainties" conveys the idea that the problem is concerned not with the discovery of a particular fact (as in traditional research), but with the comprehension or management of a reality that has irreducible complexities and uncertainties. By "decision stakes" we refer to all the various costs, benefits, and value commitments that are involved in the issue through the various stakeholders. It is not necessary for us to attempt now to make a detailed map of these as they arise in the technical and social aspects of dialogue on any particular policy issue. It is possible to identify which elements are the leading or dominant ones, and then to characterize the total system by them. This does not mean neglecting the other aspects, or ignoring the vital role that professional consulting or applied science can play in the problem in post-normal science. But it helps to know just how much revision of traditional problem-solving approaches may be necessary in any particular case.

For a simple example, we may consider dams. For a long time the location and design of dams had been seen as essentially a problem in applied science; given the needs of flood control, water storage, or irrigation, the design exercise was straightforward. Systems uncertainties could be managed scientifically, and decision stakes were those of the policymakers. With the emergence of disputes over policies for the use and conservation of water, it became clear that professional consulting was involved. The decision stakes were now part of the political process, and the various corporate interest groups employed their own experts to assist in the debate. But now that the whole rationale of dam-building is being questioned, with uncertainties and criticisms on all fronts from the hydrological to the social and religious, we are in the realm of post-normal science.

Applied science

We will now explain the three problem-solving strategies in terms of the diagram in Figure 1. We start with the most familiar one, which we call applied science, or mission-oriented research. This is involved when both systems uncertainties and decision stakes are low. The systems uncertainties will be at the technical level, and will be managed by standard routines and procedures. They will include particular techniques to keep instruments operating reliably, and also statistical tools and software packages for the treatment of data. The decision stakes will be simple as well as low; resources have been put into the research exercise because there is some particular straightforward external function for its results. The resulting information is intended to be used in a larger enterprise, which may or may not be of concern to the researcher on the job.

We should distinguish between this "applied science" and traditional "pure," "basic," or "core" science, which we can consider as "curiosity-driven" or "investigator-chosen." By definition, there are no external interests involved in such research, and so the decision stakes are very low. Also, normally such research is not undertaken unless there is confidence that the problem can probably be solved, and so normally systems uncertainties will be very low as well. By contrast, in applied science the value of a positive outcome of the research can compensate for strong uncertainty about its prospects for success. We should distinguish both these sorts of "normal science" (in the sense of Kuhn [5], in which research is devoted to solving puzzles that are assumed to have answers) from innovative or revolutionary science, in which systems uncertainties are high and, for various reasons, decision stakes as well. Thus Galileo's astronomical researches involved the whole range of issues from astronomical technique to religious orthodoxy; so even though it was not directly applicable to industrial or environmental problems, it was definitely extreme both in its uncertainties and its decision stakes. The same could be said of Darwin's work in *The Origin of Species*. In this respect there is a continuity between the classic "philosophy of nature," which was dominant before the rise of academic, positive science, and the post-normal science that is now emerging.

Professional consulting

Professional consulting, or client-serving problem-solving, is broader than applied science. It deals with problems requiring a different methodology for their resolution. Uncertainty cannot be managed at the routine, technical level, because more complex aspects of the problem, such as reliability of theories and information, are relevant. Then, personal judgments, depending on higher-level skills, are required, and uncertainty is at the methodological level. The decision stakes are also more complex, as the task in professional consulting is performed for a client, whose purposes are to be served. The goal of the task cannot be made perfectly clear, as in the case of applied science, for humans have purposes of which they are conscious, and which themselves are variable and contradictory. In the case of risks and environmental issues, the professionals may experience a tension between their traditional role and the new demands made on them, for the purposes relevant to the task are no longer those of individual clients, but will include those of various human stakeholders, personal and institutional, perhaps with discordant perceptions and values.

Professional consulting shares many features with applied science, features which distinguish them both from core science. Both operate under constraints of time and resources, with problems defined by external interests; and their products generally do not lie in the "public knowledge" domain. For much of the time the professional consultant's tasks can be reduced to exercises in applied science, as the routine work becomes standardized in technique and in the management of uncertainty. But professional consulting is different from applied science in occasionally requiring creativity, as well as the readiness to grapple with new and unexpected situations, and (most important) to bear the responsibility for their outcome. In this respect engineering belongs to professional consulting, as "engineering judgment" is a well-known aspect of the work.

As a problem-solving strategy, professional consulting has other important differences from applied science. The outcomes of applied science exercises, like those of core science, have the features of reproducibility and prediction. That is, experiments should in principle be capable of being reproduced anywhere by any competent practitioner; these experiments operate on isolated, controlled natural systems. Therefore, the results amount to predictions of the behavior of natural systems under similar conditions. By contrast, professional tasks deal with unique situations, however broadly similar they may be. The personal element becomes correspondingly important; thus, it is legitimate for a client to call for a second opinion without impugning the competence of a doctor or other professional, or implying that either of them is simply wrong. This element of professional judgment and clients' choice is most clear in the forensic context, where scientists appear as expert witnesses, displaying all their differences of interpretation and opinion.

The public may become confused or disillusioned at the sight of experts disagreeing strongly on a problem apparently involving only applied science (and the experts may themselves be confused!). But when it is appreciated that these issues involve professional consulting, these disagreements should be seen as inevitable and healthy. Occasionally, however, there is felt to be a need for consensus among professional experts, as when historic or field data are inadequate as inputs for models of industrial or environmental hazards. "Expert judgments," producing estimated quantities, are then employed as a substitute. If the experts themselves disagree strongly, the task of quality assurance is then conducted at a higher level, namely the assessment of the quality of the experts themselves! Such a process could iterate without end, leading to what we might call the "$[\text{expertise}]^n$ problem." In practice, the problem is resolved institutionally, but by the clients rather than by the community of experts. Such phenomena are a reminder that problems whose statement may appear to be those of applied science (as, the safety of a particular installation) may actually involve professional consulting; and even that may be insufficiently broad for their resolution.

Such complex problems as these remind us that quality assurance must be enriched when we go from applied science to professional consulting. We can envisage four components in the problem-solving task: the purpose, the person, the process, and the product; we can call this time "*p*-4" approach to quality assurance in problem-solving work. In core science, the main focus of attention in immediate quality assessment (as by journal referees) is on the process. For the product (the outcome of the research) is not usually reproducible except by a repetition of the research; hence the written reports of materials, instrumentation, and techniques are the objects of the referees' scrutiny. This is why quality assessment in core science must be done by peers who are experienced in research and also familiar with the topic, and it is therefore necessarily a technically esoteric activity. In applied science, the focus of assessment extends to products, and is done partly by managers and users; for it is they on whose behalf the research work is performed. Quality assurance is then less esoteric, since the users may have their own purposes, and therefore have less need to understand the research process itself. Thus in the case of applied science there is an automatic extension of the community with a legitimate participation in the evaluation process, and there is a corresponding loss of autonomy by the relevant research community. In professional consultancy, the focus of quality shifts strongly to the purpose (of the client) and to the person (of the professional).

High quality of service to clients (as based on good applied science as enriched and supplemented by professional judgment) is rewarded partly by enhanced personal prestige of the professional.

Post-normal science

We can now consider the third sort of problem-solving strategy, where systems uncertainties or decision stakes (or both) are high. When an issue in post-normal science is addressed, both professional consulting and applied science can be part of the overall activity, because not all aspects of the problem will involve high uncertainty or conflicting values. However, the professional tasks or the applied research exercises do not dominate the decision-making process.

Post-normal issues may include a large scientific component in their description, sometimes even to the point of being capable of expression in scientific language. In this sense they are analogous to the "trans-science" problems first defined by Weinberg [6]. But it seems best to distinguish the problems analysed here from that earlier definition; for Weinberg imagined problems that differed only in scale or technical feasibility from those of applied science. They were scarcely different from those of professional consultancy as we define it [7]. In the terms of our diagram (Fig. 1), post-normal science occurs when uncertainties are either of the epistemological or the ethical kind, or when decision stakes reflect conflicting purposes among stakeholders. We call it "post-normal" to indicate that the puzzle-solving exercises of normal science (in the Kuhnian sense), which were so successfully extended from the laboratory of core science to the conquest of nature through applied science, are no longer appropriate for the solution of global environmental problems.

The epistemological sort of uncertainty has become familiar to experts even where computer methods dominate the problem-solving strategy. They were already accustomed to technical uncertainty, in the "errors" of the data inputs, and to methodological uncertainty in the response of the models to the inputs (as gauged, for example, by sensitivity analyses or comparison of models). But increasingly, experts are becoming aware of the insoluble questions of what, if anything, their models have to do with the real world outside, since their outputs are generally untestable. Thus, these experts discover in their own practice an extreme form of uncertainty, which borders on ignorance. This last sort of uncertainty cannot be reduced to the methodological or technical sort, and therefore it cannot be treated by standard mathematical or computational techniques. With computer modeling as an example, we can appreciate how pervasive epistemological uncertainty is in all the scientific fields involving global environmental issues. Hitherto, such problems have been neglected because there has seemed to be no systematic solution to them. But this is a form of ignorance-of-ignorance, a most dangerous state for mankind [8].

Post-normal science has the paradoxical feature that, in its problem-solving activity, the traditional domination of "hard facts" over "soft values" has been inverted. Because of the high level of uncertainty, approaching sheer ignorance in some cases, and the extreme decision stakes, we could even interchange the axes on our diagram (Fig. 1), making "soft" values the horizontal, independent variable. A good example of such an inversion is provided by the actions that will need to be taken in preparation for mitigating the effects of sea-level rise consequent on global climate change. The "causal chain" here starts with the various outputs of human activity, producing changes in the biosphere, leading to changes in the climatic system, then to changes in sea level (all these interacting in complex ways with varying delay times); out of this must come a set of forecasts which will be the inputs to decision processes; these result in policy recommendations that must then be implemented on a broad scale. At stake may be a significant fraction of the world's urban built environment (including most capital cities) and the settlement patterns of people; mass migrations from low-lying districts may be required at some time that cannot yet be predicted, with the consequent economic, social, and cultural upheaval.

Such far-reaching social policies will be decided on the basis of scientific information that is inherently uncertain to an extreme degree; even more so because plans for mitigation must be started with a long lead time lest the rebuilding and relocation efforts start too late. A new form of legitimation crisis could emerge; for if governments try to base their appeal for sacrifice on the traditional certainties of applied science, or on the authority of professional consultancy, this will surely fail to carry conviction. Public agreement and participation, deriving essentially from value commitments, will be decisive for the assessment of issues, the setting of policy, and the acceptance of the costs. Thus, the traditional scientific inputs have become "soft" in the context of the "hard" decisions, depending on value commitments for their enactment, that will determine the success of policies for mitigating the effects of a possible sea-level rise.

The traditional fact/value distinction has not merely been inverted; in post-normal science the two categories cannot be usefully separated. The uncertainties go beyond the systems, to include ethics as well. All global environmental issues involve new forms of equity, which had previously been considered "externalities" to the real business of the scientific–technical enterprise. These involve the welfare of new stakeholders, such as future generations, other species, and the ecosystem as a whole. The intimate connection between uncertainties in knowledge and in ethics is well illustrated by the problems of biodiversity and extinctions of species, either singly or on a global scale. It is impossible to produce a simple rationale for adjudicating between the rights of people who would benefit from some development, and those of a particular species of animal or plant that would be harmed. However, ethical uncertainties should not deter us from searching for solutions; nor can decision makers now overlook the political force of those humans with a passionate concern for those of other species who cannot speak or vote.

All these complexities do not prevent the resolution of issues in post-normal science. The diagram of the three types of problem-solving strategies (Fig. 1) should not be seen statically, but rather dynamically, where different aspects of the problem, located in different zones, interact and lead to its evolution. The presence of severe uncertainties and value conflicts in the problem, and of non expert participants in the solution process, does not mean that traditional problem-solving strategies have become irrelevant In post normal science there is a pattern of evolution of issues, with different problem-solving strategies successively coming to prominence, which provides a means whereby dialogue can eventually contribute to their resolution For as the debate develops from its initial confused phase, positions are clarified and new research is stimulated Although the definition of problems is never completely free of politics, an open debate ensures that such considerations are neither one-sided nor covert And as applied research exercises eventually bring in new facts, professional tasks become more effective Ideally, there evolves a consensus on at least the scientific framework of the problem, so that the normal processes of research on scientific inputs and of negotiation on detailed policies, can then ensue

The dynamic of resolution of issues in post-normal science involves the inclusion of an ever-growing set of legitimate participants in the process of quality assurance of the scientific inputs As we have seen, in the cases of applied science and professional consultancy the peer communities for evaluation have already been extended far beyond the traditional community of researchers Because of the manifold uncertainties in both products and processes, in post-normal science the relative importance of persons and purposes in the dialogue becomes enhanced We have already noticed how the choice of experts, involving the quality assurance of their personal expertise, cannot always be solved within the institutional confines of professional consultancy itself Hence, the establishment of the legitimacy and competence of participants will inevitably involve broader societal and cultural institutions and movements For example, individuals directly affected by an environmental problem will have a more keen awareness of its symptoms (including those that are indistinct or subtle), and a more pressing concern with the quality of reassurances, than those in any other role Thus they perform a function analogous to that of professional colleagues in the peer-review or refereeing process in traditional science, which in their absence might not occur in these contexts For these reasons, post normal science requires an extended peer community, participating in quality assurance and the problem-solving process, for its proper functioning

As in any deep transition involving problems and methods in science, the present contains seeds of destruction as well as renewal Many participants in environmental conflicts may come to see scientists merely as hired guns, providing the data that "we" need and ignoring or concealing the rest, others will be impervious to any arguments and evidence that contradicts their prejudged case Are such participants legitimate members of an extended peer community? Even traditional science has always included such types, but there has been an implicit ethical commitment to integrity whereby the community as a whole has maintained the quality of its work [9] Maintaining quality, necessary for all efforts to solve global environmental issues, is a major task for the science of the future

This analysis rests on an awareness of uncertainty, ignorance, and complexity, this applies equally to our own arguments We cannot predict the precise forms of post-normal science, nor which issues or institutions will be the major foci for the development of extended peer communities However, we can be sure that the examples we have discussed, as well as the many others to be found in the literature of debate and action on environmental issues, represent the main directions that science must take in the future

CONCLUSION

In every age, science is shaped around its leading problems, and it evolves with them The new environmental issues are global not merely in their extent, but also in their complexity, pervasiveness, and novelty as a subject of scientific inquiry Up to now the rationality of basic scientific research has been taken as a model for the rationality of intellectual and social activity in general However successful it has been in the past, the recognition of global environmental issues shows that this ideal of rationality is no longer universally appropriate

The scientific process now encompasses the management of irreducible uncertainties in knowledge and ethics, and the recognition of complexity, implying the legitimacy of a plurality of perspectives and ways of knowing In this way, its practice is becoming more akin to the workings of a democratic society, characterized by extensive participation and toleration of diversity As the political process now recognises our obligations to future generations, to other species and, indeed, to the global environment, science also expands the scope of its concerns We are living in the midst of this transition, so we cannot predict its outcome But we can help to create awareness and also the intellectual tools whereby the process of change can be managed for the best benefit of humanity and the global environment

Acknowledgement—We are grateful to the anonymous referee for his diligence and zeal, which contributed to the improvement of this article

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