SCIENCE FOR THE POST-NORMAL AGE

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In response to the challenges of policy issues of risk and the environment, a new type of science—'post-normal'—is emerging. This is analysed in contrast to traditional problem-solving strategies, including core science, applied science, and professional consultancy. We use the two attributes of systems uncertainties and decision stakes to distinguish among these. Post-normal science is appropriate when either attribute is high; then the traditional methodologies are ineffective. In those circumstances, the quality assurance of scientific inputs to the policy process requires an 'extended peer community', consisting of all those with a stake in the dialogue on the issue. Post-normal science can provide a path to the democratization of science, and also a response to the current tendencies to post-modernity.

Science always evolves, responding to its leading challenges as they change through history. After centuries of triumph and optimism, science is now called on to remedy the pathologies of the global industrial system of which it forms the basis. Whereas science was previously understood as steadily advancing in the certainty of our knowledge and control of the natural world, now science is seen as coping with many uncertainties in policy issues of risk and the environment. In response, new styles of scientific activity are being developed. The reductionist, analytical worldview which divides systems into ever smaller elements, studied by ever more esoteric specialism, is being replaced by a systemic, synthetic and humanistic approach. The old dichotomies of facts and values, and of knowledge and ignorance, are being transcended. Natural systems are recognized as dynamic and complex; those involving interactions with humanity are 'emergent', including properties of reflection and contradiction. The science appropriate to this new condition will be based on the assumptions of unpredictability, incomplete control, and a plurality of legitimate perspectives.

At present, there is no agreed description of what the future will bring, but there is a general sense that much of our intellectual inheritance now lies firmly in the past. 'Post-modern' is widely used as a term for describing contemporary

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cultural phenomena;[1] it refers to an approach of unrestrained criticism of the assumptions underlying our dominant culture, and it flirts with nihilism and despair. In contrast to this, here we introduce the term 'post-normal'. This has an echo of the seminal work on modern science by Kuhn.[2] For him, 'normal science' referred to the unexciting, indeed anti-intellectual routine puzzle solving by which science advances steadily between its conceptual revolutions. In this 'normal' state of science, uncertainties are managed automatically, values are unspoken, and foundational problems unheard of. The post-modern phenomenon can be seen in one sense as a response to the collapse of such 'normality' as the norm for science and culture. As an alternative to post-modernity, we show that a new, enriched awareness of the functions and methods of science is being developed. In this sense, the appropriate science for this epoch is 'post-normal'.

This emerging science fosters a new methodology that helps to guide its development. In this, uncertainty is not banished but is managed, and values are not presupposed but are made explicit. The model for scientific argument is not a formalized deduction but an interactive dialogue. The paradigmatic science is no longer one in which location (in place and time) and process are irrelevant to explanations. The historical dimension, including reflection on humanity's past and future, is becoming an integral part of a scientific characterization of Nature.

Our contribution to this new methodology focuses on two aspects. One is the quality of scientific information, analysed in terms of both the different types of uncertainty in knowledge and the intended functions of the information. It has hitherto been a well kept secret that scientific 'facts' can be of variable quality; and an informed awareness of this human face of science is a key to its enrichment for its future tasks. Our other contribution relates to problem-solving strategies, analysed in terms of uncertainties in knowledge and complexities in ethics. When science is applied to policy issues, it cannot provide certainty for policy recommendations; and the conflicting values in any decision process cannot be ignored even in the problem-solving work itself. For quality of information, we have developed a transparent system of notations (NUSAP) whereby the different types of uncertainty that affect scientific information can be expressed. It can thereby be communicated in a concise, clear and nuanced way, among traditional and extended peer communities alike. The NUSAP approach embodies the principle that uncertainty cannot be banished from science; but that good quality of information depends on good management of its uncertainties.[3]

We use the interaction of systems uncertainties and decision stakes to provide guidance for the choice of appropriate problem-solving strategies. The heuristic tool is a set of graphical displays of three related strategies, from the most narrowly defined to the most comprehensive. Two of them are familiar from past experience of scientific or professional practice; the last, where systems uncertainties or decision stakes are high, corresponds to the practice of the sciences of the post-normal epoch.[4] One way of distinguishing among the different sorts of research is by their goals: applied science is 'mission-oriented'; professional consultancy is 'client-serving'; and post-normal science is 'issue-driven'. These three can be contrasted with core science—the traditional 'pure' or 'basic' research—which is 'curiosity-motivated'. In the area of post-normal science the problems of quality assurance of scientific information are particularly acute, and their resolution requires new conceptions of scientific methodology.

In this new sort of science, the evaluation of scientific inputs to decision making requires an 'extended peer community'.[5] This extension of legitimacy to new participants in policy dialogues has important implications both for society and for science. 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 new challenges for science 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.

Reinvasion of the laboratory by nature

The place of science in the industrialized world was well depicted by Bruno Latour,[6] when he imagined Pasteur as extending his laboratory to all the French countryside, and thereby conquering it for science and for himself. In this vision, Nature itself no longer needs to be approached as wild and threatening, but through the methodology of science it can be tamed and rendered useful to mankind. The miracle of modern natural science is that the laboratory experience, the study of an isolated piece of Nature that is kept unnaturally pure, stable and reproducible, can be successfully extended to the understanding and control of Nature in the raw. Our technology and medicine together have made Nature predictable and in part controllable, and they have thereby enabled many people to enjoy a safer, more comfortable and pleasant life than was ever before imagined in our history. The obverse side of this achievement is that it may well be unsustainable, not merely in terms of equity, but even in terms of sheer survival.

The triumph of the scientific method, deploying the technically esoteric knowledge of its experts, has led to its domination over all other ways of knowing; this applies to our knowledge of Nature, and of much else besides. Commonsense experience and inherited skills of making and living have lost their claim to authority; they have been displaced by the theoretically constructed objects of scientific discourse, which are necessary for dealing with invisible things such as microbes, atoms, genes and quasars. Although formally democratic (since there are now no formal barriers to the training for that expertise), science is in fact a preserve of those who can engage on a prolonged and protected course of education, and thereby of the social groups to which they belong. In a tradition stemming from the Enlightenment of the 18th century, the rationality of public decision making must appear to be scientific. Hence intellectuals with a scientific style (including economists *par excellence*) have come to be seen as leading authorities, indeed the possessors and purveyors of practical wisdom. There has been a universal assumption (however superficial and laced with cynicism) that scientific expertise is the crucial component of decision making, whether concerning Nature or society.

Now the very powers that science has created have led to a new relationship of science with the world. The extension of the laboratory has gone beyond the small-scale intervention typified by Pasteur's conquest of anthrax. We do not merely observe the familiar gross disturbances of the natural environment resulting from modern industrial and agricultural practices. The methodology for coping successfully with these novel problems cannot be the same as the one that helped to create them. Much of the success of traditional science lay in its power to abstract from uncertainty in knowledge and values; this is shown in the dominant teaching tradition in science, which created a universe of unquestionable facts, presented dogmatically for assimilation by uncritical students. Now scientific expertise has led us into policy dilemmas which it is incapable of resolving by itself. We have not merely lost control and even predictability; now we face radical uncertainty and even ignorance, as well as ethical uncertainties lying at the heart of scientific policy issues.

For understanding the new tasks and methods of science, we can fruitfully invert Latour's metaphor, and think of Nature as reinvading the lab. We see this in many ways; for example, our science-based technology, which for a while appeared to be a new man-made Nature dominant over the old, is now appreciated as critically dependent on the larger ecosystem in which it is embedded; and that it risks destruction of itself if that matrix becomes seriously perturbed or degraded. Similarly, the extension of modern technology to all humanity, essential if equity between peoples is to be realized under the present system, would accelerate the self-destructive tendencies of the technological system itself. Thus Nature reasserts itself on all our scientific planning, for the technical and human perspectives alike.

There have been other episodes in history when science has been transformed, when a particularly successful problem-solving activity has displaced older forms and become the paradigmatic example of science. These transformations have been identified with the names of such great scientists as Galileo, Darwin and Einstein. They have mainly affected theoretical science, because until quite recently technology and medicine were not generally influenced in the short term by the results of scientific research. The challenges to science were largely in the realm of ideas. Now, as the powers of science have given rise to threats to the very survival of humanity, the response will be in the social practice of science as much as in its intellectual structures.

Centrality of uncertainty and quality

Now that the policy issues of risk and the environment present the most urgent problems for science, uncertainty and quality are moving in from the periphery, one might say the shadows, of scientific methodology, to become the central, integrating concepts. Hitherto they have been kept at the margin of the understanding of science, for laypersons and scientists alike. A new role for scientists will involve the management of these crucial uncertainties; therein lies the task of quality assurance of the scientific information provided for policy decisions.

These new policy issues have common features that distinguish them from traditional scientific problems. They are universal in their scale and long-term in their impact. Data on their effects, and even data for baselines of 'undisturbed' systems, are radically inadequate. The phenomena, being novel, complex and variable, are themselves not well understood. Science cannot always provide well founded theories based on experiments for explanation and prediction, but can frequently achieve at best only mathematical models and computer simulations, which are essentially untestable. On the basis of such uncertain inputs, decisions must be made, under conditions of some urgency. Therefore policy cannot proceed on the basis of factual predictions, but only on policy forecasts.

Computer models are the most widely used method for producing statements about the future based on data of the past and present. For many, there is still a magical quality about computers, since they are believed to perform reasoning operations faultlessly and rapidly. But what comes out at the end of a program is not necessarily a scientific prediction; and it may not even be a particularly good policy forecast. The numerical data used for inputs may not derive from experimental or field-studies; the best numbers available, as in many studies of industrial risk, may simply be guesses collected from experts. Instead of theories which give some deeper representation of the natural processes in question, there may simply be standard software packages applied with the best fitting numerical parameters. And instead of experimental, field or historical evidence, as is normally assumed for scientific theories, there may be only the comparison of calculated outputs with those produced by other equally untestable computer models.

Despite the enormous effort and resources that have gone into developing and applying such methods, there has been little concerted attempt to see whether they contribute significantly either to knowledge or to policy. In research related to policy for risk and the environment, which is so crucial for our well being, there has been little effort of quality assurance of the sort that the traditional experimental sciences take for granted in their ordinary practice. Whereas computers could in principle be used to enhance human skill and creativity by doing all the routine work swiftly and effortlessly, they have instead in many cases become substitutes for disciplined thought and scientific rigour.[7]

Even when there is empirical data for policy problems, it is not really amenable to treatment by traditional statistical techniques. As J. C. Bailar puts it:

> All the statistical algebra and all the statistical computations are of value only to the extent that they add to the process of inference. Often they do not aid in making sound inferences; indeed they may work the other way, and in my experience that is because the kinds of random variability we see in the big problems of the day tend to be small relative to other uncertainties. This is true, for example, for data on poverty or unemployment; international trade; agricultural production; and basic measures of human health and survival. Closer to home, random variability—the stuff of p-values and confidence limits, is simply swamped by other kinds of uncertainties in assessing the health risks of chemicals exposures, or tracking the movement of an environmental contaminant, or predicting the effects of human activities on global temperature or the ozone layer.[8]

Thus, by traditional criteria of scientific method, the quality of research on these policy-related problems is dubious at best. The tasks of uncertainty management and quality assurance, managed in traditional science by individual skill and communal practice, are left in confusion in this new area. New methods must be developed for making our ignorance usable.[9] For this there must be a radical departure from the total reliance on techniques, to the exclusion of methodological, societal or ethical considerations, that has hitherto characterized traditional 'normal' science.

An integrated approach to the problems of uncertainty, quality and values has been provided by the NUSAP system. In its terms, different kinds of uncertainty can be expressed, and used for an evaluation of quality of scientific information. We have to distinguish among the technical, methodological and epistemological levels of uncertainty; these correspond to inexactness, unreliability and 'border with ignorance', respectively.[10] Uncertainty is managed at the technical level when standard routines are adequate; these will usually be derived from statistics (which themselves are essentially symbolic manipulations) as supplemented by techniques and conventions developed for particular fields. The methodological level is involved when more complex aspects of the information, as values or reliability, are relevant. Then, personal judgments depending on higher-level skills are required; and the practice in question is a professional consultancy, a 'learned art' like medicine or engineering. Finally, the epistemological level is involved when irremediable uncertainty is at the core of the problem, as when computer modellers recognize 'completeness uncertainties' which can vitiate the whole exercise, or more generally in post-normal science. In NUSAP these levels of uncertainty are conveyed by the categories of spread, assessment and pedigree, respectively.

Quality assurance is as essential to science as it is to industry; and whereas in traditional research science it could be managed informally by a peer community, in the new policy issues of risk and the environment, quality of science must be addressed as a matter of urgency. The inadequacy of traditional peer review has been extensively analysed for the different areas of core science,[11] 'mandated' science,[12] and 'regulatory' science.[13] As we see, the evaluation of quality in this new context of science cannot be restricted to products of research; it must also include process and persons, and in the last resort purposes as well. This 'p-fourth' approach to quality assurance of science necessarily involves the participation of people other than the technically qualified researchers; indeed, all the stakeholders in an issue form an 'extended peer community' for an effective problem-solving strategy for global environmental risks.

Problem-solving strategies

To characterize an issue involving risk and the environment, in what we call 'post-normal science', we can think of it as one where facts are uncertain, values in dispute, stakes high and decisions urgent. In such a case, the term 'problem', with its connotations of an exercise where a defined methodology is likely to lead to a clear solution, is less appropriate. We would be misled if we retained the image of a process where true scientific facts simply determine the correct policy conclusions. However, the new challenges do not render traditional science irrelevant; the task is to choose the appropriate kinds of problem-solving strategies for each particular case.

Figure 1 involves 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 the figure, representing the intensity of uncertainty and of decision stakes, respectively. We notice that uncertainty and decision stakes are the opposites of attributes which 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 both displayed as comprising three discrete intervals. By this means, we achieve a diagram which has three zones representing and characterizing three kinds of problem-solving strategies.

The term 'systems uncertainties' conveys the principle that the problem is concerned not with the discovery of a particular fact, but with the comprehension or management of an inherently complex reality. By 'decision stakes' we understand 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 enough for the present conceptual analysis, that it is possible in principle to identify which elements are the leading or dominant ones, and then to characterize the total systems by them.

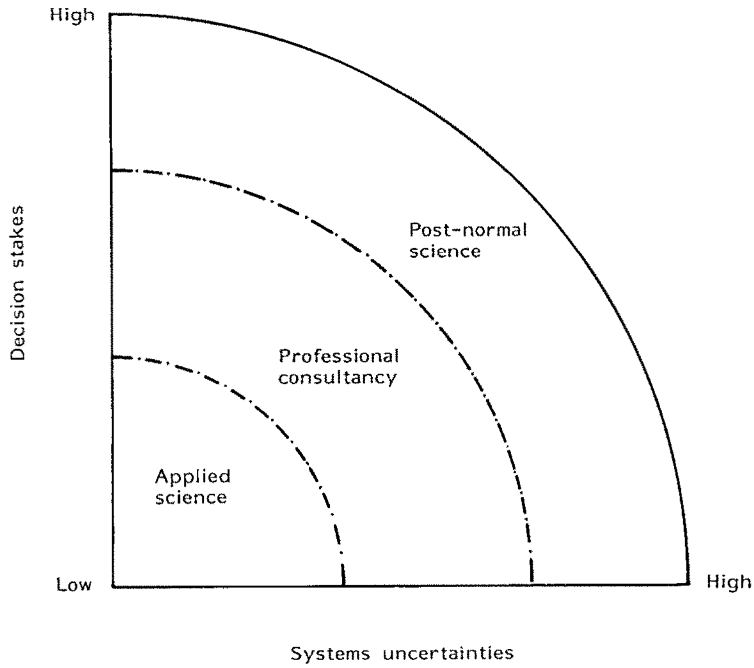

Figure 1. Problem-solving strategies

Applied science

The explanation of the diagram of problem-solving strategies starts with the most familiar strategy. We call this applied science. This is involved when both systems uncertainties and decisions stakes are low. The systems uncertainties will be at the technical level, and will be managed by standard routines and procedures. These will include particular techniques to keep instruments operating reliably, and also statistical tools and packages for the treatment of data. The decision stakes will be simple as well as small; resources have been put into the research exercise because there is some particular straightforward external function for its results. The resulting information will be used in a larger enterprise, which is of no concern to the researcher on the job. We illustrate this in Figure 2.

In Figure 2, traditional 'pure', 'basic' or 'core' science can be considered as concentrated around the intersection of the axes. By definition, there are no external interests at stake in curiosity-motivated research, so decision stakes are low. Also, the research exercise is generally not undertaken unless there is confidence that the uncertainties are low, that is that the problem is likely to be soluble by a normal, puzzle-solving approach. Clearly, highly innovative or revolutionary research, either pure or applied, does not lie within this category, since the systems uncertainties are inherently high, and for various reasons the decision stakes are also. 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

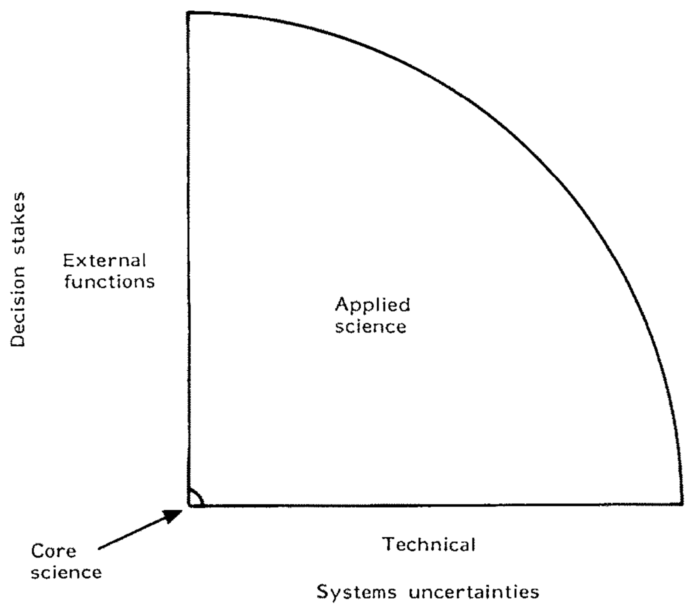

Figure 2. Applied science

the classic 'philosophy of nature' and the post-normal science that is now emerging.

We can usefully compare core science and applied science in relation to quality assurance. Where both uncertainties and external decision stakes are both low, the traditional processes of peer review of projects and refereeing of papers have worked well enough despite their known problems. However, when the results of the research exercise become important for some external function, the relevant peer community is extended beyond one particular research community, to include users of all sorts, and also managers. The situation in quality assessment becomes more like that of manufacturers and consumers, bringing different agendas and different skills to the market. For an example of how criteria of quality can differ between producers and consumers, we may consider product safety; a rare accident may be less significant to manufacturers (especially if product liability laws are lax) than for consumers. In the case of applied science, a result validly produced under one set of conditions may be inappropriate when applied to others; thus if measurements of a toxicant are given as an average over time, space or exposed populations, that may be adequate for general regulatory purposes, but that set-up could ignore damaging peak concentrations or harm to susceptible groups.

It frequently happens that the results of an applied science project are not 'public knowledge', freely available to all competent users, but rather are 'corporate know-how', the 'intellectual property' of the private business or state agency that sponsors the research exercise. If the information is relevant to some policy issue, the tasks of quality assurance may become controversial, involving conflicts over confidentiality; and the decision stakes may be raised over that non-scientific aspect. Then, the actual problem-solving strategy is no longer applied science, for the issue may involve struggles over administrative and political power, and constitutional principles of 'right to know' of citizens (for example, concerning

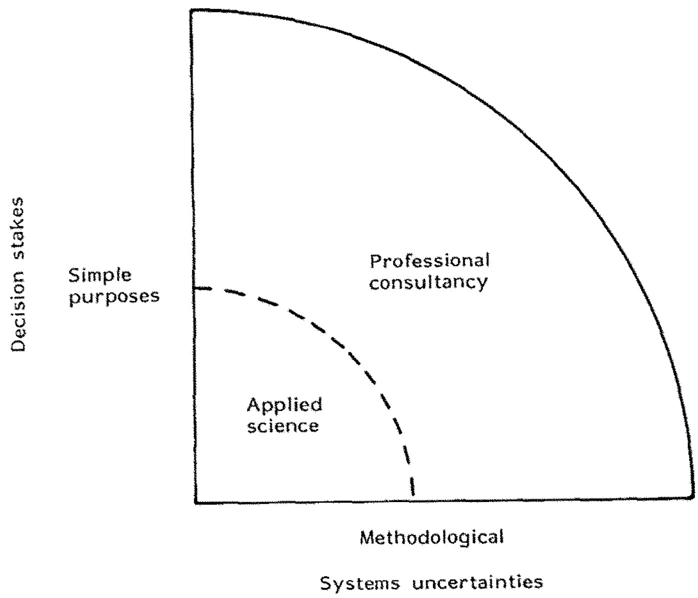

Figure 3. Professional consultancy

environmental hazards or technological risks). The relevant peer community is thus extended beyond the direct producers, sponsors and users of the research, to include all with a stake in the product, the process, and its implications both local and global. This extension of the peer community may include investigative journalists, lawyers and pressure groups. Thus a problem which may appear totally straightforward scientifically can become one which transcends the boundaries of applied science, giving rise to a more complex problem-solving strategy, such as 'post-normal science'. When scientists with a traditionalist outlook bemoan the bad influence of 'the media,' it is sometimes because of their difficulty in comprehending this new feature of science when it is involved in policy.

Professional consultancy

The diagram for professional consultancy (Figure 3) has two zones, with applied science nested inside. This signifies that professional consultancy includes applied science, but that it deals with problems which require a different methodology for their complete 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. Traditionally, the professional task is performed for a client, whose purposes are to be served. These cannot be reduced to a clear, perfectly defined goal, for humans are not machines or bureaucracies, and are conscious of their own purposes. In the case of risk and environmental policy issues, the professionals may experience a tension between their traditional role and new demands. For the purposes relevant to the task are no longer the simple ones of clients, but will be in conflict, involving various human stakeholders and natural systems as well.

The relation between systems uncertainties and decision stakes are well illustrated by the task of incorporation of error-costs in a decision. For exercises in applied science, these are generally subsumed implicitly in standard statistical methods. Confidence limits, and bounds for the two types of inference-errors, are normally employed at pre-set constant values, without reflection. But in professional tasks, error-costs may be so large as to endanger the continuation of a career. Hence they must be treated as risks, where some calculation may be employed but where judgment will necessarily predominate. When in a forensic situation, the professional will need to take account of the burden of proof for the particular problem, which will reflect the values of a particular society (whose harm is the more important to be prevented?). The same consideration holds for any policy issue; thus a problem of environmental pollution will be handled differently depending on whether a process is deemed safe until proved dangerous, or *vice versa*. Alternatively, we might ask whether absence of evidence of harm is interpreted as evidence of absence of harm. Although such methodological issues are quite beyond the ken of applied science, in professional consultancy they strongly condition all the work; and the simple descriptions as given here do not encompass the subtleties of burden of proof as it is used in practice.

Professional consultancy shares many features with applied science, distinguishing them both from core science. Both operate under constraints of time and resources, with projects funded and mandated by external interests; and their products frequently lie outside the 'public knowledge' domain. For much of the time professional tasks can be reduced to routine exercises, as the work becomes standardized in its technique and in the management of uncertainty. But professional consultancy involves the readiness to grapple with new and unexpected situations, and to bear the responsibility for their outcome. Engineering is on the border between the two, for most engineering work is done within organizations rather than for individual clients; and yet the problems cannot be completely reduced to a routine, so that 'engineering judgment' is a well known aspect of the work. Of engineering we could say that most routine engineering practice is a matter of empirical craft skills using the results of applied science, while at its highest levels it becomes true professional consultancy.

A contrasting intermediate case is that of the role of the 'expert'. This is normally someone who advises, but whose responsibility is defined by his position as an employee; hence it is not the client's interest that defines his role but that of his employer. In that respect, his decision stakes are simpler than those of the professional consultant, and the systems uncertainties as he sees them are correspondingly reduced. It is possible for a single individual to occupy these three roles, alternately or even (to some extent) simultaneously, giving rise to confusion among his audiences or perhaps even for himself! An academic researcher may give advice on a policy-related issue; his prestige and legitimacy derive from his reputation in research, either in core science or applied science; he assumes the authority of the professional consultant when offering his judgments; and if his research is too closely controlled by some funding organization, then in fact he might be acting as an expert on their behalf. This is why the possibility of 'conflict of interest' is raised when scientists make public pronouncements, without anyone impugning their personal integrity as perceived by themselves.

As a problem-solving strategy, professional consultancy has 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, any experiment should in principle be capable of being reproduced anywhere by any competent practitioner, for they operate on isolated, controlled natural systems. Therefore the results amount to predictions of the future behaviour of natural or technical 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 to call for a second opinion without questioning the competence or integrity of a doctor in a medical case. Alternatively, who would expect two architects to produce identical designs for a single brief? In the same way, it would be unrealistic to expect two safety engineers to produce the same model (or the same conclusions) for a hazard analysis of a complex installation. The public may become confused or disillusioned at the sight of scientists disagreeing strongly on a problem apparently involving only applied science (and the scientists may themselves be confused!). But when it is appreciated that these policy issues involve professional consultancy, such disagreements should be seen as inevitable and healthy. The gain in clarity should more than compensate for the loss of mystique of scientific infallibility.

This last phenomenon reminds us of the differences in quality assurance that emerge when we extend from applied science to professional consultancy. We can envisage four components in the problem-solving task; the process, the product, the person and the purpose. This is the 'p-fourth' approach to quality assurance mentioned above. In core science, the main focus in the task of quality assessment is on the process; the assessment is made on the basis of the research report, and it requires a community of subject-specialism peers (who can 'read between the lines' of the research report) for its performance. In applied science, the focus of assessment extends to products, and is done by users, for it is on their behalf that the research exercises are done. Quality assurance is then not so esoteric, since the users have less need to understand the research process; and thus there is an automatic extension of the community with a legitimate participation in evaluation. In professional consultancy there can be no simple, objective criteria or processes for quality assurance (beyond simple competence). The clients become an important part of the community that assesses quality of work, although they have no relevant technical expertise. Thus in these three cases, we see an expansion of the 'peer community' involved in quality assurance. In this respect, the 'extended peer community' of post-normal science is a natural continuation of this tendency.

Post-normal science

We now consider the third sort of problem-solving strategy, where systems uncertainties or decision stakes are high (Figure 4).

The policy issues that drive post-normal science 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 announced by Alvin Weinberg.[14] But it seems best to distinguish the problems analysed here from that earlier class; 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.[15] In the terms of our diagram, post-normal science occurs

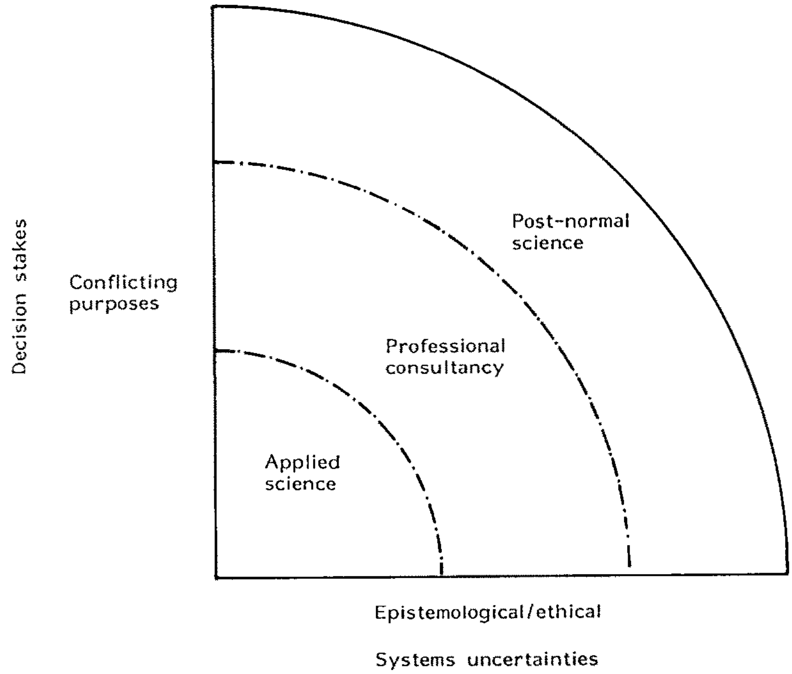

Figure 4. Post-normal science

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 to the conquest of Nature, are no longer appropriate for the resolution of policy issues of risks and the environment. We notice that in Figures 2–4, applied science appears three times and professional consultancy twice. Do these labels refer to the same things when they are included in a broader problem-solving strategy as when they are standing alone? In the sense of their routine practice, yes. But when they are embedded in a broader problem-solving strategy the whole activity is reinterpreted. The problems are set and the solutions evaluated by the criteria of the broader communities. Thus post-normal science is indeed a type of science, and not merely politics or public participation. However different from the varieties of problem solving that have now become entrenched and traditional, it is a valid form of enquiry, appropriate to the needs of the present.

Examples of problems with combined high decision stakes and high systems uncertainties are familiar from the current crop of policy issues of risk and the environment. Indeed, any of the problems of major technological hazards or large-scale pollution belong to this class. 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 might even in some cases interchange the axes on our diagram, making 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 changes in sea level (all these interacting in complex ways with varying delay-times). Out of all this must come a set of forecasts which will provide the scientific inputs to decision processes; these will contribute to policy recommendations that must then be implemented on a broad scale. But all the causal elements are uncertain in the extreme; to wait until all the facts are in, would be another form of imprudence. At stake may be much of the built environment and the settlement patterns of people; mass migrations from low-lying districts could be required sooner or later, with the consequent economic, social and cultural upheaval.

Such far-reaching societal 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 so that the huge rebuilding and resettlement programmes can get under way. The rise in sea level would not be like a slow tide, but more likely in the form of floods of increasing frequency and destructiveness. Unprepared harbour cities (as most of the world's political and financial centres) could be devastated. A new form of legitimation crisis could emerge; for if the authorities try to base their appeals for sacrifice on the traditional certainties of applied science, as on the model of Pasteur, this will surely fail. Public agreement and participation, deriving essentially from value commitments, will be decisive for the assessment of risks and the setting of policy. Thus the traditional scientific inputs have become 'soft' in the context of the 'hard' value commitments that will determine the success of policies for mitigating the effects of a possible sea-level rise. In this way we see how the 'systems' involved in environmental policy issues are truly 'emergent', comprising dimensions of cognition and value which transcend those of the systems studied by traditional systems theory and its modelling techniques. Thus post-normal science corresponds to an enriched systems theory, deriving analytical rigour from it, and providing it with experience and insights.

The traditional fact/value distinction has not merely been inverted; in post-normal science the two categories cannot be realistically separated. The uncertainties go beyond those of the systems, to include ethics as well. All policy issues of risk and the environment involve new forms of equity, which had previously been considered 'externalities' to the real business of the scientific–technical enterprise, that is the production and consumption of commodities. These new policy issues involve the welfare of new stakeholders, such as future generations, other species, and the planetary environment as a whole. The intimate connection between uncertainties in knowledge and in ethics is well illustrated by the problems of extinction 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 species of animal or plant which would be harmed. However, the ethical uncertainties should not deter us from searching for solutions; nor can decision makers overlook the political force of those humans who have a passionate concern for those who cannot plead or vote. Only a dialogue between all sides, in which scientific expertise takes its place at the table with local and environmental concerns, can achieve creative solutions to such problems, which can then be implemented and enforced. Otherwise, either crude commercial pressures, inept bureaucratic regulations, or counterproductive protests will dominate, to the eventual detriment of all concerned.

All these complexities do not prevent the resolution of policy issues in post-normal science. The diagram should not be seen statically, but rather dynamically; different aspects of the problem, located in different zones, interact and lead to its eventual solution. 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 science exercises eventually bring in new facts, professional consultancy tasks become more effective. A good example of this pattern of evolution is lead in petrol, where despite the absence of conclusive environmental or epidemiological information, a consensus was eventually reached that the public health hazards were not acceptable. Such a resolution does not always come quickly or easily; some substances might be called 'yo-yo risks' because of the way they go up and down in the experts' perception; Dioxin seems to be one such. In those cases, effective public policy would be better based on an appreciation of the inherent uncertainties rather than on the illusion that *this* time applied science has given us the true verdict of safe or dangerous.

Extended peer communities

The dynamic of resolution of policy 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 applied science and professional consultancy the peer communities are already extended beyond those for core science. In post-normal science, the manifold uncertainties in both products and processes require that the relative importance of persons becomes enhanced. Hence the establishment of the legitimacy and competence of participants will inevitably involve broader societal and cultural institutions and movements. For example, persons directly affected by an environmental problem will have a keener awareness of its symptoms, and a more pressing concern with the quality of official reassurances, than those in any other role.[16] Thus they perform a function analogous to that of professional colleagues in the peer-review or refereeing process in traditional science, which otherwise might not occur in these new contexts.

On occasion, the legitimate work of extended peer communities can even go beyond the reactive tasks of quality assessment and policy debate. The new field of 'popular epidemiology' involves concerned citizens doing the disciplined research which could, or perhaps should, have been done by established institutions but was not.[17] In such cases they may encounter professional disapproval and hostility, being criticized either for lacking certified expertise or for being much too personally concerned about the problem. The creative conflict between popular and expert epidemiology not only leads to better control of environmental problems; it also improves scientific knowledge. A classic case is 'Lyme disease', where local citizens first identified a pattern in the vague symptoms which later characterized a previously unknown, but not uncommon tick-borne disease.

When problems lack neat solutions, when environmental and ethical aspects of the issues are prominent, when the phenomena themselves are ambiguous, and when all research techniques are open to methodological criticism, then the debates on quality are not enhanced by the exclusion of all but the specialist researchers and official experts. The extension of the peer community is then not merely an ethical or political act; it can positively enrich the processes of scientific investigation. Knowledge of local conditions may determine which data are strong and relevant, and can also help to define the policy problems. Such local, personal knowledge does not come naturally to the subject-specialism experts whose training and employment predispose them to adopt abstract, generalized conceptions of genuineness of problems and relevance of information. Those whose lives and livelihood depend on the solution of the problems will have a keen awareness of how the general principles are realized in their 'back yards'. They will also have 'extended facts', including anecdotes, informal surveys, and official information published by unofficial means. It may be argued that they lack theoretical knowledge and are biased by self-interest; but it can equally well be argued that the experts lack practical knowledge and have their own unselfconscious forms of bias.

The new paradigm of post-normal science, involving extended peer communities as essential participants, is clearly seen in the case of AIDS. Here the research scientists operate in the full glare of publicity involving sufferers, carers, journalists, ethicists, activists and self-help groups, as well as traditional institutions for funding, regulation and commercial application. The researchers' choice of problems and evaluations of solutions are equally subjected to critical scrutiny, and their priority disputes are similarly dragged out into the public arena. There are some costs; thus it is no longer easy for scientists to exercise their benevolent dictatorship over passive test subjects in the 'double-blind' procedure where some get no treatment. But unless we believe it right that the sufferers from this dread disease should depend entirely on the zeal and dedication of researchers, manufacturers and regulators, they should be included in the dialogue, however fractious it may sometimes become.

As yet, such cases are still the exception. Extended peer communities generally operate in isolation, on special policy issues in isolated localities, with no systematic means of financial support, and little training in their special skills. On many occasions, there is insufficient competence in dialogue and communication with other stakeholders.[18] Recognition of their role is very variable; in the USA, with its traditions of devolution of power to the local level, 'intervenors' in some decision processes are provided with support; in other countries they may be ignored or actively hindered. Within such extended peer communities there will be the usual tensions between those with special-interest demands, and the outside activists with a more far-reaching agenda, along with the inevitable divisions along lines of class, ethnicity, gender and formal education. However, all such confusion is inevitable, and indeed healthy, in an embryonic movement which is fostering the transition to a new era for science. It could be that the field of health, where individual 'consumer preferences' can operate more effectively on a mass scale than in environmental policy issues, the rise of post-normal science will occur more smoothly. 'Complementary medicine' could in many ways be considered a type-case for post-normal science; and in spite of the inevitable external opposition and internal confusions, it grows steadily.

It is important to appreciate that post-normal science is complementary to applied science and professional consultancy. It is not a replacement for traditional forms of science, nor does it contest the claims to reliable knowledge or certified expertise that are made on behalf of science in its legitimate contexts. The technical expertise of qualified scientists and professionals in accepted spheres of work is not being contested; what can be questioned is the quality of that work in these new contexts, especially in respect of its environmental, societal and ethical aspects. Previously the ruling assumption was that these were 'externalities' to the work of science or technology; and that when such problems arose an appropriate response would somehow be invented by 'society'. Now the task is to see what sorts of changes in the practice of science, and in its institutions, will be entailed by the recognition of uncertainty, complexity and quality within policy-relevant research.

As in any deep transition, the present contains seeds of destruction as well as renewal. Some participants in environmental struggles come to see scientists merely as hired guns, who should provide the data that 'we' need and consent to the suppression of the rest. Others will be personally impervious to any arguments and evidence that weaken 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.[19] The maintenance of quality, without which all efforts to solve policy issues of risk and the environment are doomed, is a major task for the methodology of the science of the future.

Conclusion

In every age, science is shaped around its leading problems, and it evolves with them. The new policy issues of risk and the environment are global not merely in their extent, but also in their complexity, pervasiveness, and novelty as a subject of scientific inquiry. Until now, with the dominance of applied science, the rationality of reductionist natural-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 the policy issues of risk and the environment shows that this ideal of rationality is no longer universally appropriate.

The activity of science now encompasses the management of irreducible uncertainties in knowledge and in ethics, and the recognition of different legitimate 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 recognizes 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 rapid and deep transition, so we cannot predict its outcome. But we can help to create the conditions and the intellectual tools whereby the process of change can be managed for the best benefit of the global environment and humanity.

The democratization of this aspect of science is not a matter of benevolence by the established groups, but (as in the sphere of politics) the achievement of a system which despite its inefficiencies is the most effective means for avoiding the disasters that result from the prolonged stifling of criticism. Recent experience has shown that such a critical presence is as important for the solution of the policy issues of risk and the environment as it is for society. Let us be quite clear on this; we are not arguing for the democratization of science on the basis of a generalized wish for the greatest possible extension of democracy in society. The epistemological analysis of post-normal science, rooted in the practical tasks of quality assurance, shows that such an extension of peer communities, with the corresponding extension of facts, is necessary for the effectiveness of science in meeting the new challenges of global environmental problems.

This analysis is complementary to that of our previous article on post-modernity.[20] Both deal with the loss of hegemony of a single worldview based on a particular vision of science. The post-modern phenomenon is one of a deepening disillusion and a consequent fragmentation at all levels including the ideological and the societal. One reaction, as among some leading exponents of post-modernity, is despair. Another reaction is to reassert 'normality'; thus some leading scientists claim that the solution of our ecological problems lies through funding their large programme of relevant basic research, in which uncertainty is never mentioned.[21] Indeed, the suppression of uncertainty in 'normal' science makes it compatible with quite extreme reactions to the contemporary condition; thus it has been noticed that some religious fundamentalists find no difficulty in practising scientific expertise of various sorts, as the two dogmatisms can, with appropriate boundary drawing, coexist comfortably.[22] Finally, the post-normal response is to recognize the challenge, with all its dangers and promise; and then to start towards a reintegration, through the acceptance of uncertainty and the welcoming of diversity. In a later article we will discuss these various trends.

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