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THE POETRY OF THERMODYNAMICS

Energy, entropy/exergy and quality

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The new thermodynamics of non-equilibrium and complex systems enables a greater understanding of natural processes, including ecosystems and life. To the classic variables of Energy and Entropy, it adds Exergy. Its development comes at the same time as an enhanced awareness of the social and cultural aspects of natural science. Combining these two trends, we explore the possibility of the enrichment of our understanding of both predominantly natural and predominantly cultural ('reflexive') systems through their poetry. For this, the concept of Quality serves for the synthesis of systems thinking.

In recent years the concepts of the new thermodynamics have been used to achieve a synthesis of various facets of complex systems, including the physical, ecological, and economic.[1] A recent issue of *Futures*[2] was devoted to this theme. Here, we further develop this work, distinguishing among systems that are simple, complex, and reflexive. We suggest that as Energy mainly characterises the state of simplicity, and Entropy/Exergy that of complexity, there is a third property, which we will call Quality, mainly characterising reflexivity. (All concepts apply in some degree to each systems level). The latter concept enables us to express the dialectical character of reflexive systems in particular, and it also highlights the inherent anthropocentrism of all concepts in both systems theory and thermodynamics. With Quality, we make explicit the connection between the disciplined study of thermodynamics and its poetry.

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Our approach enables distinction among the modes of enquiry that are appropriate for different aspects of the world, thereby avoiding the modern errors of reductionism along with the ancient errors of anthropomorphism. By this means we are also able to gain perspective on those approaches whose proponents have used the mantle of Science to proclaim them as universal and exhaustive. It also provides a philosophical foundation for a new form of scientific practice, appropriate to the needs of a world in which simplicity is a memory of a bygone age, and in which reflexivity characterises all the systems that we need to understand and manage.

This new scientific practice is based on the tasks of quality assurance in the new contexts of issue-oriented science. In traditional science, quality assurance was accomplished by largely informal means, within a relatively homogeneous peer community. Now, when dialogue on issues is characterised by a plurality of perspectives, the quality assurance of scientific inputs requires the self-aware (and possibly conflicting) participation of an 'extended peer community'. The scientific tasks themselves can no longer effectively be conceived as simple, for they are embedded in institutional and societal contexts, which condition both the various actors and the conceptual objects of enquiry that are studied. Hence all the elements of the scientific task are complex, and the scientists themselves must become reflexive. We can no longer maintain the previously taken-for-granted background assumptions of the simplicity of problems and the exclusive legitimacy of reductionist scientific rationality. Scientists, like all other participants in the dialogue, must reflect on their own condition, as one among the interests that make up the social order. In these post-normal conditions science operates, as it were, in a multi-cultural environment; its criterion for success can no longer be an idealised simple truth, but rather a realistic complex and reflexive quality.

Simple, complex and reflexive systems

The vision of modern Western science, from its origins, has been one of the simplicity of the world to be studied. Descartes attempted to reduce physics to matter in motion, and psychology to the reactions of mechanisms and particles. The accepted model for reasoning was geometry; and the stated aim was to enable the control of the whole natural world by routine operations, like those of the mechanic. Ever since then, developments in science have been counted as advances if they further articulated that paradigm of simplicity. Its model has been of individuals conceived rather like Hobbes' atomic persons; and it eventually enabled the exclusion of design and purpose from biological explanations. Descartes' 'beau roman de physique' (as his disillusioned follower Huygens called it) finds its contemporary manifestation in that biological science which finds anything bigger than a cell too complicated to be a worthwhile object of study.

Even now, in the world of affairs (and particularly in the sciences that serve it) quantity is a surrogate for certainty. Quality must be reduced to numbers if it is to be respected.[3] It matters little that genuine quality of performance, even at the practical level, is distorted and betrayed by numerical accounting tricks. Eventually, the corruptions of quality in human social intercourse can lead to an oscillation between fragmentation and hegemony, the models for the desperate visions of Hobbes and Orwell. Countering this sort of entropy–decay of quality requires purposeful human action, imbued with compassion and with an understanding that sees beyond a billiard-ball universe.

A simple intellectual system may be characterised by its scientific properties (eg linearity of its defining equations); but it is best to see simplicity in terms of possibility of effective capture by routine cognitive operations. For there are some systems whose behaviour is not 'simple' in that technical sense (such as those studied by chaos theory), and yet which do not pose any challenge to the reductionist programme of science. To be sure, some such systems are genuinely complicated, perhaps having many variables, or non-linear operations, so that they defy the neat, formal solutions of the paradigm of classical mathematical physics. However, we shall consider the 'complicated' systems as falling within the class of essentially simple systems. The term 'capture' is of course highly anthropomorphic; it comprehends both theory and practice, and is relative to the goals of those studying or manipulating the system, and we know that no system is 'purely' simple; for any real system (material or intellectual) has a history, embedded in social processes of creation and use; but pragmatically we can say that many are, and are certainly conceived as, simple in this sense.

The difference between simple and complicated systems is one of degree; in the case of a complicated system, some skill and judgement are required for its effective capture. In the practice of science, a simple system is the sort provided for students' exercises; a project requiring original thinking is complicated. The pendulum provides a good example of the different sorts of system embodied in a single conceptual object. As the subject of a mathematical exercise, the 'simple pendulum' is defined through both physical idealisation and mathematical simplification. Students learn that its period of oscillation is independent of the amplitude of its swing, and they can derive and calculate the dependence of period on length, but when the un-simplified mathematical equations of the physically idealised pendulum are used, they do not yield a neat solution. Some skill and judgement are then required for the decision as to whether that 'complicated' idealised physical pendulum is, in any given context, adequately represented by the mathematically simplified 'simple' pendulum.

The pendulum can also serve as an illustration of systems with greater complexity. Pendulums, as manufactured and used in clocks, are part of a complex socio-technical system of timekeeping, with its own criteria of quality in production and use. To complete the picture, the development of the pendulum was partly motivated by considerations in the 'reflexive' domain. Throughout its use as a timekeeper it performed functions for astronomy and navigation, and thereby served exploration and conquest.

We should expect that the task of defining complexity should itself be complex. Considering complexity from the experience of biology, we might define such systems in terms of hierarchical structure, exergy-degrading process, and multiple space–time scales. All other properties, such as anticipation, goal-seeking, historical uniqueness, adaptation, self-regeneration and evolution, and multiplicity of perspectives, could then be explained in terms of those particular chosen fundamentals. Within those terms, a fruitful graduation of types of complex systems is: passive, adaptive, self-renewable, evolutionary, and self-aware.

Alternatively, when we consider complexity from an abstract, mathematical approach, the property of multiplicity of perspectives can be taken as fundamental.[4] This property also serves well for a definition within an epistemological approach. Among complex systems we find organisation and structure, with a diversity of elements, relationships and subsystems. Whereas simple systems have no teleology (although there can be unidirectional processes, as in Fourier's theory of the flow of heat), complex systems may have a hierarchy of functions. There are also overall systems goals like survival and growth. Whether goals and functions 'really' exist in natural complex systems is not relevant here; we find that for their explanation, the reductionist programme of simple-systems natural science is definitely inappropriate.

There is a broad range of degrees of complexity. In the context of terrestrial evolution, at the lower end are the chemicals of the supposed primordial soup. These are provided with shape by the physical forces of their environments, and then through their structures they combine and change, to engage in an evolutionary process towards ever more elaborate forms and ultimately to genuine life. The complex molecules that have become familiar in recent decades, as genetic materials and viruses, are on the borderline of genuine complexity. For some purposes they can be treated as mere collections of atoms; but we put resources into their study because of their importance in relation to our own purposes. Hence while the objects themselves may be considered as simple systems, they affect us because they are parts of complex systems; and as our study of them is inevitably selected and shaped by our concerns, our knowledge of them is part of the reflexive system including ourselves, our societies and our beliefs.

Fully developed living systems, as organisms or ecosystems, will have an intricate fabric of relationships, which we unavoidably caricature with our concepts of competition and co-operation, and of predation, parasitism and symbiosis. Such rigid categories reflect our own expectations and predispositions, and so our theories of complex systems are to that degree in the reflexive domain. Thus, a predator species culls the stock of the prey species, and thereby maintains its quality; so in that respect it is a symbiote as much as a species whose members exhibit obviously co-operative behaviour. Even apparently catastrophic events, like forest or prairie fires, are now understood as being part of the long-term cycle for species which experience them. This more dialectical understanding of complex systems has produced the concept of a cycle including 'creative destruction',[5] as a replacement for the old idea of a permanent 'climax culture'.

Systems created with a conscious design, that is artefacts, might be considered as genuinely complex; that judgement will depend on the interaction that is envisaged. Thus a motorcycle is designed to be simple in use and maintenance, requiring only adherence to simple rules in both cases. Robert Pirsig's 'Phaedrus' (in *Zen and the Art of Motorcycle Maintenance*)[6] decided to interact reflexively with his own motorcycle, employing subtle skills in diagnosis of its operations and also philosophical introspection about that process. This was in conscious contrast to the practice of his friend, who simply turned in his bike to the garage for a service whenever one was due. Phaedrus found that from his perspective the motorcycle system was complex:

> For example, the feedback mechanism which includes the camshaft and cam chain and distributor exists only because an unusual cut of this analytic knife. If you were to go to a motorcycle parts department and ask them for a feedback assembly, they wouldn't know what the hell you were talking about. They don't split it up that way. No two manufacturers ever split it up quite the same way, and every mechanic is familiar with the problem of the part you can't buy because you can't find it because the manufacturers consider it a part of something else. (p.72)

Some artefactual systems require skill and judgement in their ordinary operation; most industrial equipment is of this sort. Then the 'system' cannot be considered as mere machinery, but for its effective operation must be envisaged as including the technical, social and personal dimensions all together and interacting. For example, the system necessarily includes rules, or 'standard operating procedures', which themselves embody technical materials as shaped by relations of responsibility and power, expectations of behaviour and also ethical principles. The possibility of 'accidents' introduces further dimensions of reflexivity, since 'safety' is itself a recursive concept (involving hierarchies of control). In addition, 'safety' exists partly as a personal construct among those affected and thereby possesses highly paradoxical properties. A 'safe' system is liable to induce complacency and hence increase risk, a phenomenon known as a type of 'moral hazard'. Thus, a full analysis of such artefactual systems, which for some purposes can be considered as just machines, leads to an awareness of paradoxes and contradictions of the same depth as those at the foundations of mathematics and logic.[7]

In such reflexive systems of artefacts, the piecemeal evolution of the system takes place through a 'patching', either of its hardware or of its defining procedures, as a result of learning. Sometimes this latter operation is done routinely, as in computer programs; but sometimes there are components of the system (either individuals or groups at various holarchic levels) which resist the proposed change. Then change is accomplished either through conflict, or surreptitiously. This latter tactic is quite common; in any such system, it is well known that operatives regularly need to break the established rules in order to keep the system running. The convenient practice of industrial sabotage through 'working to rule' illustrates how rules tend to drift out of correspondence with their ostensible function, and must be broken or at least bent if the system is to operate. This process constitutes a challenge to those who set the rules, and yet it is essential to their survival. Thus a reflexive system may well be characterised by the necessity of 'insubordination'. Thus reflexive systems like these possess an inner dynamic which threatens instability in order to preserve effectiveness. Such processes can help to explain why, as we have discussed elsewhere,[8] reflexive systems tend to a state of oscillation between hegemony and fragmentation (tyranny or anarchy) in their social aspects. In the thermodynamic analogy, such an oscillation constitutes an 'entropic' state. It is all too easily seen among nations of the so-called 'less developed' world. Its prevention requires special systems for the injection of the reflexive analogue of exergy, which we call quality.

Energy, entropy and exergy

As it is traditionally introduced in science teaching, the energy concept is presented as an objective feature of the natural world, whose laws are independent of human activity. It is measured through physical variables which themselves are defined in mechanical terms ('work' and then 'force'); and its fundamental property is given by the First Law, stating its conservation through all changes of form. In our terminology, this amounts to conveying this theory as if it were a simple conceptual system. Of course, that is an oversimplification; starting with Mach,[9] historians and philosophers have shown that the concepts and their names have rich histories, in which (apparent) clarity emerged only fitfully from confused practice, incomplete theory, and poetry. Its lineage comes from one of the many senses of 'force', in this case a 'living force' or 'vis viva' associated with moving bodies. As this was clarified in the early nineteenth century, the constancy of conversion factors between different sorts of 'force' became noticed, and then a Greek word was imported to describe that basic substance, itself unobservable, which remains unchanged in quantity through all its changes in form.

The obscurities at the foundations of Newtonian mechanics could be successfully suppressed for many generations (Mach's analysis appeared nearly two centuries after the Principia), but in thermodynamics they were patent from the outset. The struggle for realisation of the Energy concept and the First Law was bound up with paradoxes out of which came the Second Law. The conservation of energy was first seen as an equivalence among conversions, such as that between the heat of friction produced in water descending a waterfall (measured by Joule on his honeymoon) and the work done by the condensation of steam in an engine. But while some conversions seemed capable of conversion either way (as between chemical and electrical reactions), the conversion to low temperature heat seemed irreversible. Although the energy remains unchanged in quantity, it is somehow degraded in quality. In the steam engine (the first technological model for the science of thermodynamics) the work seems to be done by the fall in temperature of the working substance, heat. However, the paradox is more easily visualised through a water-wheel. We see falling water caught by the wheel, which (driven by the weight of the water) then turns on its axle. This motion, appropriately transformed by gearing, drives a shaft. This rotational motion is transmitted to the machinery of a mill. There the energy coming from the waterfall is eventually dissipated as heat, noise, and wear-and-tear on materials. Although the energy is conserved, and necessarily still exists, it can no longer be applied to useful work. It is 'different'; and this difference in the energy requires another concept for its characterisation. (This example was first developed by Cardwell.[10])

The difference was first described in terms of 'entropy' (literally, directionlessness), and mathematical arguments showed how, under certain conditions, a reaction converting heat to work would always increase this rather strange quantity. The scientist who first gave a clear formulation to this Second Law promptly proceed to do poetry with it. Rudolf Clausius generalised from the properties of idealised heat engines to those of the entire universe. To a popular audience he told a story of a 'heat death' of the universe, occurring some time in the unimaginably distant future, when the entropy will have risen to its maximum possible and no more work can be done.

Later, clarification was achieved by J. Willard Gibbs, who produced a comprehensive theory of the modes of conversion of energy. He distinguished between entropy and another function, 'free' or available energy, later called exergy. In the simple reactions described above, the two are related in a simple inverse fashion. Thus as entropy increases through the various reactions, exergy (available energy) decreases; and when (within the boundaries of the particular system), entropy has reached its maximum, exergy is zero. This simple relationship has produced confusion, for otherwise, particularly in modern thermodynamics, the concepts are quite distinct. With the development of the kinetic theory of gases, there seemed to be a physical realisation of entropy, as 'disorder' and then 'ignorance' and even 'subjectivity'. Such interpretations were then taken over into the modern theory of information. However, this approach to entropy has been critically scrutinised, and found to rest on confusions.[11] Conversely, exergy has established its distinct theoretical position in the thermodynamics of far-from-equilibrium systems.

A closer look at the simple example of the waterwheel provides us with some important insights. The first is that even this very simple, perhaps rudimentary example, embodies anthropocentric perspectives. All cycles of conversion of energy are equivalent in two senses: that the energy is conserved throughout, and that it is degraded in the process. But there are important differences among them. What happened to the potential energy of the water as it went over that waterfall, before the waterwheel was built there? Given the two possibilities (waterwheel in place, or not), the potential energy could be realised in different ways: one as the highly structured energy of rotation, the other as the largely random motion of turbulent fall. In this latter case, some of the energy becomes heat as the water hits the pool, and some becomes kinetic energy of the flowing stream below. But it has done no 'useful work' on the way down; and from this particular anthropocentric point of view, that conversion process is of 'lower quality'. So it is correct to say that while scientifically all energy conversions are equal, anthropocentrically some are more equal, that is useful, than others.

Another way of looking at the overshot water wheel is to see how it preserves a structure in the body of water which is carrying the energy of the waterfall. As the water is caught in the wheel's shaped blades, it collects in parcels, and by the force of gravity produces a steady rotational force which is transmitted to the shaft. Gently lowered by the wheel, the water has little kinetic energy as it is released, and it splashes softly in the pool below. By contrast, in the unimproved waterfall the water tumbles down, more or less broken up by the lip of the retaining wall, perhaps being further disturbed by air resistance and wind, and it finally crashes into the pool at the base, forming chaotic eddies before being carried off downstream. The transformation process lacks organisation, and this is a sign of the degradation of the energy. The water's brief transition from top to bottom of the waterfall has had no structure, and no 'useful work' was done. In that sense its energy transformation is of low anthropocentric quality.

Considerations of structure help us to appreciate the importance of exergy in the analysis. Returning to the case of the waterwheel, where 'useful work' is produced, we consider the waterwheel itself as part of the energy-flow pattern. How did it get there? Clearly, someone used energy (or rather, exergy) in creating a structure that had not been there before. The structure was then used in the modification of the process of the descent of the water, so that the maximum useful energy was extracted during it. In the unimproved waterfall, the water arrives at the bottom with a reserve of kinetic energy, ready to splash and eddy; but it leaves the waterwheel with scarcely more available energy than that of the pool into which it merges. However, the structure of the waterwheel is also part of that nexus of energy modification; through use it becomes degraded, needing repair and eventual replacement. So the waterwheel extracts and passes on the maximum exergy from the falling water, only by itself having absorbed exergy in its construction and maintenance. The inclusion of the waterwheel constitutes a first enrichment of the energy-flow picture; for the moment we do not enquire into those who built it and why, but we are reminded that energy is not about simple degradation, but involves structures and renewal as well.

This aspect of exergy enables us to suggest a poetry for it, complementing those of energy and entropy. Energy, one of whose definitions almost echoes that of a deity ('that which can be neither created nor destroyed') serves to do work and thereby sustain the system in which it operates. 'Entropy' brought a new insight into the philosophy of nature, perhaps even more fundamental than unidirectional time: the inevitability of dissolution and hence of death. Its name ('no-direction') implies the presence of something beyond the matter-and-motion of the dogmatic materialists; for structure can be degraded and lost only if it is there to begin with. These two principles already carry us a long way to explaining how things are. From the simplest Bénard cell, producing its honeycomb of convective cylinders of water, up to the solitary mystic who nonetheless breathes and eventually dies, all of nature exhibits work and structure, and permanence and decay.

But there is renewal as well. Early thermodynamics did not provide us with a principle for the explanation and scientific study of such phenomena as renewal and life.

Exergy fills that need; with it, we can explain far-from-equilibrium systems, and life itself. Now we can allow our metaphors to play up and down the scales of complexity of systems, without falling into either the anthropomorphism of the ancients or the reductionism of the moderns. We will show how analyses of biological and human or social systems can illuminate each other, without either sort being denuded of its distinctive features. For a poetry of this triad of principles, we have the Great Game of the Hindu cosmos, presenting Brahman, Vishnu and Shiva as creator, sustainer and destroyer respectively. This seems to be a richer vision than that of the polarities of Yin and Yang, which can seem to oscillate inconclusively. And the new scientific vision of ecosystems, abandoning an eternal 'climax' and accepting cycles that include 'creative destruction'[12] fits well with that Hindu vision of cycles upon cycles, in which destruction here becomes creation there.

The thermodynamics of life

Among the creators of the science of thermodynamics were men who had strong commitments both to the improvement of industrial practice and to the cultivation of the philosophy of nature. By some of them (though not by all!) thermodynamics was interpreted as an expression of a materialistic philosophy, which was intended to show the way that the world is and has to be. With its foundation in theory and experiment, it was utterly convincing, but there was an apparent exception to the universal law of degradation of energy and structure in all transformations—life. It could be explained away, as a curious temporary and local aberration; but given our own unavoidably anthropocentric perspective, it could not be called insignificant. It took about a century before thermodynamics began to catch up with life, and that happened when an implicit restriction on all previous thermodynamic theories was relaxed. This was the assumption that the processes studied were all at or near 'equilibrium'. Without this assumption, the mathematical tools that were until then available could simply not have been applied. But with the assumption of equilibrium, the science of thermodynamics was restricted in its scope, to systems where the forces driving a reaction are very nearly balanced by those resisting it, and are hence very nearly reversible.

In recent decades new methods for studying reactions far from equilibrium have been developed. For these, let us now recall the waterwheel example, but imagine it in accelerated time-frame, so that the waterwheel needs nearly constant maintenance. Then we have a system in which energy is attenuated (from that of gravity to rotational motion, wear-and-tear, and waste heat), producing the maximum of exergy en route, but requiring a parallel set of energy-exchanges. In those, exergy is used for the re-creation of the structures which guide and constrain the process. If the repair work is not done properly, the wheel will (for example) start to leak, and more water escapes and less exergy is extracted. If for some reason maintenance is not kept up, then eventually the wheel will seize up and stop. The system then reverts to that of a waterfall, with some intermediate pauses as water lands on the overflowing stationary buckets. Although not at a thermodynamic equilibrium, the waterwheel system has (to a good level of approximation) turned into a 'natural' simple state, with no new structures being created out of materials and no exergy being extracted during the process.

The waterwheel example will take us only so far, as it does not deal with heat and chemical energy-exchanges. But these far-from-equilibrium systems are basically similar, in that everything happens as if they are extracting as much useful work as they can from the energy, by increasing its flow along gradients, or pathways of decreasing intensity, so that what is emitted at the end is of as low an intensity as possible. A most dramatic experimental example of this is in the Bénard cell, in which a mass of water, as it absorbs heat, will (under certain conditions) organise itself into separate columns where hot water rises and cooler water falls, smoothly and efficiently. Equally dramatic is the ecological example of a forest, whose emitted heat is at a much lower temperature than that of grassland or of land without vegetation.[13] In such systems, the eventual stopping of the waterwheel has its analogue in the tendency of the whole system to revert to equilibrium. In this state there would be no pathways of attenuating energy, or gradients, and hence no extraction of energy.

In the case of 'life' as we know it on Earth, the source of intense high-quality energy is the sun; and the energy no longer usable in the metabolic cycle is emitted as low-grade heat, just as in the original steam engine. Living systems employ a parallel cycle of materials and structures which enable their chemical reactions to proceed and reproduce. Complexity is created in photosynthetic processes by the intense input energy, and is then destroyed to provide feedstocks for the various cyclic reactions. The sun is an 'absolute' with respect to the earth-system, as we do not affect its source (although we can very much affect the energy transmitted from it to ourselves); and also because its time-scale of change is much greater than those of human history and biological evolution.

So life turns out to have its own thermodynamic structure; but it is very different from the temporary, anomalous phenomenon imagined by the science that took its inspiration from the steam engine. The popular term 'edge of chaos' well expresses the contradictions involved in sustaining the special conditions enabling its existence. The sun is a necessary condition for life, but not at all sufficient; its rays can destroy as well as nourish, destroying quality more easily than creating it. These insights were used by James Lovelock when he realised, from the presence of special trace gases in the upper atmosphere, that our planet is an unstable system, far from equilibrium. A planet exhibiting classical thermodynamic behaviour would be Mars.

Complexity and the dialectics of energy

The processes of life can now be understood in terms of the new thermodynamics, and in addition we gain a better grasp of the behaviour of energy as it flows in Nature. Our first picture of the transformations of energy is a good example of how a reflexive reality is mapped down onto simple systems. Although we did mention the anthropocentric aspects of the waterwheel model and its concepts, still when we described the process we allowed the image of an essentially simple and quantifiable process. This preconception has been responsible for many failures in the field of analysis of environmental energy; good scientists have assumed that the task of measuring the flows of energy as it is transformed must necessarily be straightforward; the only problem was to find that particular indicator which would display the process most clearly and usefully.

As a matter of practical experience, quantifying these flows through all their branches cannot always be done to any useful degree of accuracy. Therefore, the use of energy models for policy cannot be one of simple determination as is possible in a system of lower dimensions. The technical reason for this can be seen both in the difficulties of measurement of flows in particular cases, and also as the impossibility of imputing a partition of energy flows where streams diverge, in the absence of measurements. Hence what appears to be at first (as in the case of the water-wheel) an uncomplicated branching of energy (falling water, plus rotating axle, that in turn becoming energy in machines, and then friction and heat), turns out to resist complete quantification. When the energy coming into a complex system is immediately taken up in living processes, close quantification of all transformations becomes strictly impossible. Indeed, although useful aggregate estimates can be and are routinely made, every particular action of transformation of energy in the natural world is complex in our sense, and therefore profoundly ambiguous to our understanding.[14]

Energy flows can no longer be depicted as occurring along simple downhill paths. This new vision is even more necessary when we consider life as other than an inconvenient exception to the majestic Second Law, and appreciate it is a major partner in the work of shaping the planet. Rather, we find webs of energy transformation, like those of material transformation, with multiple paths in and out of any nexus, with intensification as well as remission. Finally there is a causality that is very far from linear, where even cycles (physiological and environmental) are an over-simplification. If we want to escape from the metaphorical confines of the Industrial Revolution, and have an evocative image of energy for the age of reflexivity, we might think of a wave in the ocean surf, where form is created and dissipated simultaneously, in a process where determinism and chaos are at play.

Thus energy in the environment becomes like any other environmental variable, subject to deep uncertainty and unpredictability. Its study then resembles, in principle, that of systemic events which can be analysed only in retrospect, as is the case with disasters. In studies of this sort, where linear causal thinking cannot master the problems, we see the outlines of what would be a science of reflexive systems. The use of such studies in policy is totally different from the classical model of scientific research, which is assumed to yield assured conclusions which themselves entail correct policy options. Instead, we have Post-Normal Science. In this, complexity is respected through its recognition of a multiplicity of legitimate perspectives on any issue; and reflexivity is realised through the extension of accepted 'facts' beyond the supposedly objective productions of traditional research. Also, the new participants in the process are not treated as passive learners at the feet of the experts, being coercively convinced through scientific demonstration. Rather, they will form an 'extended peer community', sharing the work of quality assurance of the scientific inputs to the process, and arriving at a resolution of issues through debate and dialogue.

Systems and natural philosophy

The poetry of the new thermodynamics conveys different, more lively images than the old. Previously the discourse was about a single machine, or reaction, or discrete phases; now it concerns structures, cycles, systems, and feedbacks (positive as well as negative): complex wholes with their own histories and even explicit anthropocentric evaluations. The term 'system' has become indispensable, as it conveys something about the sort of complexity that is not mere complication or confusion. A special vocabulary has been invented to give articulation to this insight. Along with 'subsystems', we speak of 'hierarchies', usually of aggregation or scale, but perhaps also of structures and relationships. Within hierarchies there are 'holons' (as introduced by Koestler[15] expressing the dialectical character of systems. For each of these things is 'a whole which is also a part'; and relations between individual holons and those at lower and at higher levels have tensions of opposed sorts. Generally speaking, causal relations with higher levels will involve functions and reasons (and perhaps purposes too), while those at lower or parallel levels will tend more to physical, or mechanically causal relations. Within the Systems approach it is quite scientific to speak of reflexive properties, such as life, society, and consciousness.

In order to identify where reductionist approaches are effective, and where not, we invoke a model of a multi-dimensional space, whereby we can imagine a rich system including nature, life and society. This is clearly a metaphor, as we do not imagine 'dimensions' of the physical sort to exist in the systems we study; but then all of systems terminology is a metaphor, validating itself by the heuristic power of its insights. We might refer to them as 'hierarchical dimensions', as a reminder both that we are not dealing with physical space, and also that qualitative distinctions are involved. The holons in the lower hierarchical dimensions will be those studied by the quantitative methods of physical science, and where only complication can arise. Then come those hierarchical dimensions with complexity, such as life; and at the top are those with the properties characteristic of reflexivity, such as purpose and awareness. The hierarchical dimensions with reflexivity are also characterised by indeterminacy and uncertainty (sometimes deep); and hence ethics becomes necessary for the self-aware beings there. It is important to keep in mind that this latter sort of beings, including ourselves, are also holons, that is systems comprising several hierarchical dimensions, including lower-dimensional subsystems, and also relating to other holons in all directions. For an earlier version of such a model, we might imagine Leibniz's system of 'monads', all perceiving each other in a system of pre-established harmony; to that we add an explicit differentiation among degrees of realisation of existence.

In this 'phase space' metaphor we can speak of 'stable lower-dimensional manifolds', which are slices across reality where the higher attributes of holons are excluded from view. These represent the objects of reductionist science (natural and social) ever since its origins in the metaphysical atomism of Descartes and Hobbes. Such lower-dimensional manifolds, in which the behaviour of conscious beings can be observed or represented as if they were complex or even simple systems, can be very important for scientific study. Regularities in the behaviour of conscious beings, most remarkably in the stable population frequencies of individually rare actions, even suicides (first analysed by Quetelet in the early nineteenth century), have provided the reductionist approaches to social behaviour with much of their plausibility.

A very rich ground for natural philosophy now is that middle area of complex systems, including living systems. Here sophisticated reductionist approaches can provide real insights, and even nourish the hope that they can capture the whole, yet somehow that whole has always eluded explanation by reduction. To this end, computer simulations of evolutionary processes are made, in the never-ending hope of seeing the emergence of qualitative novelty, and not mere quantitative difference; that is, a real Origin of Species. The theories of complexity and chaos inhabit these ambivalent fields, their challenge calls for a response which must necessarily comprehend the powers of reductionism in its proper domain. In order to do this we must explore the complementary domain within the total multi-dimensional phase space, that of reflexive systems.

We can also use the phase space metaphor to illuminate some long-standing paradoxes of human knowledge, particularly in science. Anyone who has studied science textbooks was exposed to the deep difference between that sort of learning and any other. In natural science textbooks, all is impersonal, and all is certain. Values are absent from view, and equally invisible are disagreement, doubt and plurality of interpretations. The textbook implicitly promotes science as 'objective knowledge', agreeing with generations of propagandists who have promoted science as the superior, or even the only, form of genuine knowledge. Of course, anyone who has been involved in syllabus development knows how the selection and shaping of the scientific material to be taught is conditioned by value-commitments and conflicts, sometimes quite fierce. But all of that subjectivity is then carefully concealed from the students, as it usually is from the public.

However, in recent times we have had the experience of ignorance and error on a significant scale, mainly in connection with the environment but also health, originating with scientists and their communities, and presumably therefore from science itself. Such public and well-publicised imperfections in the edifice of scientific knowledge cannot even be conceived within the framework of traditional philosophies of science. One approach to an explanation of their occurrence is to consider the sub-systems in which these various activities operate. Textbooks of science generally purport to deal with Nature only, in hierarchical dimensions that are simple or at most complex; reflexivity is absent from view. Similarly, the data from experience obtained in scientific research do not themselves tell of their context in the reflexive hierarchical dimensions; as recorded they are only bald, simple numerical or verbal statements. It is only when the data are interpreted as evidence, and are assessed for their quality in the context of the inferences in which they are employed, that they are seen as involving reflexivity. By contrast, a competent research paper will at least provide a sketch history of the evolution of its problem as a human creation. But traditional philosophies of science had the programme of bypassing such human influences, in the quest to find a basis for certainty in science. In reaction, the recent wave of demystifying accounts of scientific practice have tended to go from naive certainties to cynical denials of cognitive certainties in the product of social and of ethical certainties in the process.

With an historical perspective on the whole process, we can appreciate both the historical triumphs and the present difficulties of science. We can say that traditional science focused on the problems it could solve, which tend to be the easier ones located in the stable, lower-dimension manifolds of the systems phase space. But with the emergence of issues of risks and the environment, we have salient scientific problems thrust upon us whose very statement involves reflexivity as well as the full complexity of ecological systems. Problems about the future, be they of the climate, of radioactive wastes, or drug-resistant pathogens, are all about how humanity, with our given socio–technical systems, can adapt in order to survive. For such problems, we need a new conception of science, one which comprehends these higher hierarchical dimensions of reflexivity.

Thus what could once be seen as a perfect 'objectivity' of science, and presented as such in textbooks and popularisations, is now understood as knowledge whose scope is restricted to simpler, lower-dimension manifolds of the systems phase space. We know from experience that even though such knowledge is historically and socially conditioned in many ways, it is still not 'arbitrary'; and so the post-modern critique of science need not hold. But for the establishment of the genuineness of scientific knowledge, traditional unreflective methods and approaches to science, based on the assumption of simplicity, are inadequate; and traditional philosophies of science are irrelevant. Post-Normal

Science, with its emphasis on uncertainties, value-commitments, plurality of perspectives, dialogue, and quality, provides a way forward.

Quality—unbound and bound

The enrichment of the thermodynamic concepts to include exergy enables us to comprehend processes of renewal, such as life, which lie in the middle hierarchical dimensions of the systems phase space. But for reflexive systems, with their mixture of radical creativity and innovation with radical instability and decay, another image is desirable. With this in mind, we suggest quality as a complement to the other three principles. Like those principles, it always applies at all hierarchical dimensions of the phase space; but quality uniquely characterises reflexive systems.

The term is already rich in connotations. Etymologically it relates to the choice or definition of a thing, but now it most commonly refers to goodness of some sort. Recently, through Pirsig[16] its numinous aspect has been emphasised. With the introduction of this nomenclature we make inescapable our own belief in the fundamental unity of science with philosophy and poetry. If reductionism related only to Nature, that would be bad enough; but it also induces a false consciousness about our study of Nature, truncating all awareness of that study as a human endeavour. With quality we announce a different conception of science, both natural and social, one which has evolved beyond reductionism both in thought and in practice.

Our discourse about Quality cannot proceed on familiar lines of definition, either logical or operational. We know enough of the history of scientific thought to be aware that all representations are incomplete; but Hegel said, theories conceal as much as they reveal. As we have learned even in connection with scientific concepts such as energy and entropy, formal definitions have been, and indeed must be supplemented by parables. Unfortunately Pirsig, who introduced quality to popular discourse, tried to move from the parables of *Zen and the Art of Motorcycle Maintenance* to the formal definitions of *Lila*[17] losing not merely the haunting quality of the original but also the force of its message. Here we will proceed to elucidate Quality by a method of comparison and contrast with the other principles.

We recall how energy works, in sustaining the system of life on earth. Coming from its absolute source outside, it proceeds through its successive transformations as it drives cycles of material change, producing work of various sorts and in the process sacrificing its intensity, and thus (if you wish) its own quality. As it goes from being intense radiation, passing through various chemical forms, and eventually becoming background heat, it retains its quantity (First Law) but is degraded in quality through the increase of entropy (Second Law). In the new thermodynamics, the renewal of structure is explained through the workings of exergy, moving energy along gradients of decreasing intensity. This process, characteristic of complex rather than simple systems, provides a metaphor for quality. We can also imagine a flow outwards of quality from a source, on the analogy of energy, in which it interacts dialectically with its own sort of entropy and is renewed by infusions of its own sort of exergy. Persistence of quality in its pure form is impossible; indeed original quality is so ephemeral, that the tension between its emergence and its diffusion produces one of the great contradictions of civilised life. But on the analogy of exergy, quality can also be conserved and re-created, as it threads its path through reflexive systems.

For an example of such processes of decay and recovery, which in a sense constitute the history of creativity and culture, let us take a great production of the human spirit, such as a masterwork of painting. Its creation is normally compressed into a relatively brief span of time, and the artist usually makes a single decision that it is 'complete'. (This of course depends on the cultural context; it is mainly in modern European culture that the products of personal creation have an atomised existence, so that they can be claimed as the sole intellectual property of the atomic individuals who are accepted as their creators, and eventually sold to become the legal property of the atomic individuals who are accepted as their purchasers.) However, as soon as the masterwork begins to interact with the world of ordinary matter and mundane minds, its quality is altered and in some respects denatured. Sometimes this happens with dramatic thoroughness, as in the case of Leonardo's Last Supper, which was painted with experimental materials on the (less prestigious) damp north wall of a chapel in Milan, started to deteriorate noticeably within a few years, suffered numerous restorations over the centuries, had its chapel nearly demolished by Allied bombs in World War II, and was thereby exposed to dust, water and cold. The quest for a restoration of the real, historical Last Supper may be as impossible as that for the historical Jesus; but when confronted with this patched and battered relic, the viewer may participate in its quality, going through an aesthetic experience so intense that it can border on the mystical. Indeed, we may characterise works of true genius by this property of the strong persistence and even renewal of their original quality through all contingencies and vicissitudes. Otherwise, the quality of a creation generally attenuates, as the work is reproduced, translated to other contexts, made accessible, and generally submits to all the other processes of diffusion, decay and oblivion, through which it makes its unique contribution to human culture.

Unlike in the case of simple systems with energy and entropy, the process is not all one of attrition; the historical trajectory of genuine quality will necessarily include rejuvenation. Changes in cultural context and in experienced realities may bring about a renewal and even a re-creation of meaning. Of course, any self-conscious reconstruction will seem a violation to some, as the historically evolved quality is displaced or destroyed; and in hyper-sophisticated times like our own, even the nature of 'authenticity' becomes a contested issue. This property of perpetual rejuvenation and rebirth in new contexts could be a defining characteristic of true quality in a creation. We see it with the dramatic works of Shakespeare and of the classical Greek tragedians. Works of scientific genius also share this apparently paradoxical property; and so knowledge itself can be reconsidered, away from the atomistic conception that has been dominant hitherto in our civilisation.[18]

Because novelty is more common (on the anthropocentric scale of perception) at the upper, reflexive hierarchical dimensions of the phase–space system, it is easier for us to perceive quality there, just as (for us) energy predominates at the lower hierarchical dimensions. But there are no absolute barriers. In a sense, quality is present whenever a Benard cell forms, and energy is required for the bodily sustenance of a genius as well as for the diffusion of her productions. Among the structures to which the mathematics and poetry of entropy has been applied are those which carry information. The principle is that content decays with every transition. It is exemplified in the interpretation of ancient manuscripts, to establish lines of descent; there it is assumed that copyists introduce, rather than correct, errors. Modern information technology has analogous processes of entropy-increase. For software always decays in use (thus losing quality), and it can also be locked in to hardware 'platforms' that age and deteriorate inexorably. The approaching crisis over computer systems not designed to cope with the year 2000 is a reminder of how a technology which ignores entropy will become its victim.

There is another parallelism between the workings of energy and of quality. It is overly anthropocentric to imagine that high-intensity energy, coming into a cycle, is in some way better than the 'degraded' low-intensity energy that leaves it. Indeed, it expresses a Western bias in the whole conception of energy in the world, for in its terms events like the Indian monsoon are inferior, since in spite of its size and importance, it operates with energy in an already attenuated form, on low differentials of temperature. Such scientific metaphors have great influence on the framing of policy for industry and development, the identification of such a bias is left to those outside the dominant culture,[19] or perhaps to those who are inside but detached from it. An awareness of the inescapable metaphoric aspect of all scientific terminology can help us to frame new terms with sensitivity. For a replacement of 'degradation', the Medieval scholastics' term 'remission' as an opposite to 'intention' may be too archaic (though it still survives for diseases, notably cancer), but we might speak of 'attrition' instead.

Can we pursue the analogy further? Energy, for our life on this planet, has its absolute source in the sun. What then, if any, is the absolute source for quality? One possible answer is waiting, in philosophies which speak of emanation of Reality, from neoPlatonism to Hegel. We need not accept this vision, any more than Darwinian biologists need to believe in design in order to justify their use of teleological language. But the theory developed here, based on scientific rather than on mystical experience, provides us with a new appreciation of the role of quality in that conception of the real.

Quality and a new view of systems

There are some strong differences between the workings of energy and of quality, arising from their different main loci of operation. The higher, reflexive hierarchical dimensions of the whole system are 'emergent'; they include properties of purpose and awareness, they are to some extent even defined by continuous novelty, and concepts like 'pathological' can be applied to them. So, whereas energy generally (with the temporary exception of the behaviour of dissipative structures) is attenuated as it is transformed, the path of quality includes the potential of re-creation, or degradation, in emerging new forms.

Those who (from above) wish to control the activities of a particular holon will tend to evaluate its quality in simpler, standardised terms; in some contexts they may even believe that it can be quantified along the same lines as energy. (The assessment and then grading of achievements of students exhibit these tendencies, along with the contradictions that inevitably arise.) In social systems, efficiency (along with effectiveness) in the performance of tasks is a common attempted measure of quality. This was the attribute, well quantified in industrial practice, which provided the theoretical framework for early thermodynamics. But its object, the steam engine, was presumed to work in a simple, stable environment, effectively restricted to the lower hierarchical dimensions of our systems phase space. The quantification of quality of human performance is fraught with pitfalls, well analysed by the master of industrial quality, W. Edwards Deming, who helped Japanese manufacturing industry rise to world dominance during the decades he was ignored in the West.[20]

In the case of holons at higher hierarchical dimensions, there is a complementarity of adaptability with efficiency at every level of systems operation, except perhaps the most simply mechanical. An examination of adaptability reminds us of the need to conceive systems as hierarchical entities. For each holon must be robust against changes in the inputs from lower levels (the material and efficient causes of Aristotle), and also flexible against requirements (demands and constraints) from higher levels (the formal and final causes). Such dynamic relationships distinguish the genuinely systemic hierarchies from the quantitative hierarchies based on scale or aggregation.

The trade-off between efficiency and adaptability is exhibited in the Holling cycle for ecosystems (the 'lazy-eight' figure),[21] where the 'climax' phase has maximised efficiency of throughput at the expense of loss of robustness against external shocks. This is a mechanism for enabling the creative destruction of natural systems. We notice that the systems component producing the shocks (fire, flood, etc) while at the same scale of aggregation and size is effectively a holon at a lower hierarchical level, being simpler in its constitution and actions. This distinction is quite crucial in reflexive systems, where vulnerability to shocks is the most obvious price for one-sided economic efficiency (as the case of non-sustainable socio–technical systems).

The quality of reflexive systems also has a strong inbuilt tendency to degeneration, realised through its own form of entropy. The more exalted the inspiration and purpose of an institution at its foundation, the more vulnerable it is to stultification by the very routines that become necessary to keep it going in ordinary circumstances. This contradiction has been described as that between 'prophets' and 'priests', or between St Francis and Brother Elias; and Dostoyevky's 'Grand Inquisitor' explained it with sufficient clarity for all time. Priest and prophet are complementary in their functions; and their operations are based in different holarchic levels. The prophet is necessary as an occasional stimulus to rejuvenation and even flexibility, while the priests are necessary for the ongoing maintenance of efficiency. The prophet works personally at a higher holarchic level; but by his actions and style he can unleash destructive forces operating at lower levels, against which the general social system may not be sufficiently robust. Priests may therefore be constrained to act in a harsh and unprincipled way against the prophet, for the protection of the vulnerable flock. This dialectical relationship between quality and permanence should not be interpreted as an instruction for institutions and movements to 'aim low', but rather for us to understand how tragedy can be part of the human condition.

In the terms of our theory of reflexive systems, we can imagine constitutional government as a sort of design exercise, involving criteria both at the complexity level (flexibility, efficiency, robustness), and also at the reflexivity level (justice, liberty). The Lockean design solution for the preservation of quality in civil government included 'representative democracy' and 'separation of powers'. In this, there is a regular 'creative destruction' of one part of the system (the representative legislature) through elections, acting to prevent the stagnation and corruption of the whole. In that fashion, it was hoped to avoid the fragmentation of excessively democratic societies, such as classical Athens, and the hegemony (itself unstable and very hazardous in transition) of a divinely sanctioned monarchy.

Of course, quality, as a social category, requires its own governing. In that process, its systemic and reflexive character is clearly displayed. The old Latin motto, 'Quis custodiet custodes ipsos?' (Who guards the guardians?) is a reminder that control cannot be complete at any given hierarchical level, but iterates upwards without a definite end. This is why even apparently technical exercises must ultimately be under political control, lest the relevant institutions adopt their own quality regime at the expense of the wider good. Then there will be debate over the criteria and procedures to be adopted for quality assurance; on a variety of issues there will be design choices along the spectrum from the informal to the formal. After immersion in the raw practice of quality assurance in some particular field, one might be tempted to view the whole process as an exercise of subjectivity. But that would be to ignore the constraints of the external world, and the influences of history and of morality, on practice in this area as well as any other.

The dialectics of quality are shown even more clearly in the hazards of attempts to preserve it in human social life. Political revolutions regularly and necessarily devour those of their children who advocate permanence of the revolutionary situation (Robespierre, Trotsky, Che Guevara); and those who try to re-create the quality of the original moment of creation (such as in Mao Tse Tung's Cultural Revolution) head for disaster. An analogy for the quality of the energy-cycle, in the realm of reflexivity, would be the effectiveness of the diffusion of quality through the culture. Experience shows that it is vain to hope for a 'climax culture' of a permanent steady-state flow of quality. Mere diffusion and spreading is not sufficient for maintaining its continuous flow from the creative source. For quality, like liberty and other human values, must be made afresh in every generation, through creative struggle. In the absence of that renewal, entropy will conquer, and we can speak of a cultural desert. In it, the masses subsist on productions in which quality is present only in a meretricious form, and real creativity becomes a precious (and therefore deformed) possession of a self-conscious isolated elite. Then there is no process whereby the original quality, the source of creativity, works through to those varied audiences whose acts of appreciation or mastery create new experiences, and hence new creations, of quality.

This degenerate condition can be realised in broader culture, as in the triumph of 'consumerism'. Instead of a healthy 'civil society' of a diversity of free associations of citizens, where quality (civic and aesthetic alike) is diffused, we have an all-enveloping market that seduces its captive audiences with all sorts of novel synthetic fantasies, made ever more vivid and addictive through information technology.[22] This condition can (at least for a while) coexist with formal democracy in the political sphere. Providing a more effective opiate than institutional religion ever could, it masks the hegemony whereby the traditional oppressive societies maintained their stability; although the irreducible 'underclass' and the arrival of crime as a world-class economic force are evidences of fragmentation that cannot be Disneyed away. This ultra-consumerism is the state which has provoked some, at least, of the post-modern criticisms. Its inner contradictions could be realised through the collapse of quality of workmanship in the technical infrastructure which is essential for the dominant high technology of spectacle.[23]

Over the past few centuries in Europe, and at an accelerating pace in recent decades, we have been extending quality, as an attribute, to ever larger domains of Nature. This amounts to a fundamental change of direction in the flow of quality, which in traditional societies was from Nature inwards to humanity; this had been called 'animism'. In modern times, starting with the liberation of slaves, men began to share human dignity with other classes, as women, children, and aliens; by now we have now moved to embrace not only pets and higher mammals, but trees, butterflies and generations of all species as yet unborn, culminating in Gaia herself.

Such an indefinitely expanded solidarity, extending an anthropomorphic quality to the cosmos, has contradictions which have called forth new emergent structures of organisation and increasing complexity. For in the natural world, while individual beings may not like to be eaten by others, the short run there is not much that they can do about it; and the system's changes are usually limited to quantity. Pain and death are the inseparable concomitants of enjoyment and life. Human cultures which accept this reality can kill with compassion, respect and even grief, as part of their total interaction with their related 'other' species.[24] However, in our contemporary civilisation, pain and death of any sort, to any being, are deemed as needing to be reduced as much as possible, always and everywhere. The commitment to a universal spreading of quality encounters the contradiction of indeterminable boundaries: cetaceans are nice, but mosquitoes too? The impossibility of resolving this particular contradiction can lead to sentimental activism.

The attempts to conserve quality for individuals, unchanged and free of contradiction, manifests within our affluent societies as an inability to cope with pain and death. It can lead to grotesque results. Safety, comfort, convenience, and above all entertainment have become the overriding goals of consumer technological design. In the technologies of the person, this tendency has the consequence of the commodification of beauty, youth and life itself (either the delaying of death or the technological production of offspring). Runaway technologies, driven by marketed sentimentality, are now producing true 'cyborgs' in which new sorts of being are created. The historic tendency of puzzle-solving science to conceive itself on the lower hierarchical dimensions of the system has over the past half century led to new and more threatening problems, as resistant pathogens, long-lived nuclear wastes, and Year 2000. What grotesque and monstrous conceptions will be achieved by commercialised cyborg technology, remains to be seen.

Reviewing the two tendencies described above, we see that the first is committed to the universalisation of quality, while the second strives for its freezing, holding entropy at bay. They should be understood as interacting with the previously mentioned technology of spectacle, which attempts to replace quality by psychedelia. Each in its own way represents an attempt to eliminate the vital distinctions within the real world that allow quality to play. The distinctions between the qualitatively discrete hierarchical systems of artefact, nature and human have become blurred. To cope with this cultural novelty, new, more reflexive systems of thought and organisation are required, lest all the systems collaborate in mutual and self-destruction.

Conclusion

We can learn much about our own predicament from the interactions of the four thermodynamic principles, Energy, Entropy/Exergy, and Quality. In our culture, quality is increasingly embodied in sophisticated matter–energy systems, rather than in inherited cultural forms. Our civilisation thus depends on massive throughputs of energy, transformed at a frantic rate by an enslaved technological quality, and producing entropy at an accelerating pace. This latter manifests partly in the lower, material hierarchical dimensions, as the 'wastes' or 'pollution' that threaten to poison or choke our industries, cities, and selves. It is also there in the higher hierarchical dimensions as the loss of 'quality of life', a staleness of social existence, the creation of profoundly alienated masses, and of a constantly threatening degeneration of the functional quality of the support systems, both material and social, on which we all depend. The injections of exergy, in the form of ever more complex systems intended to prevent or remedy these structural ills, carry their own costs, and can eventually overload the societal system and contribute to its collapse, as in the case of declining civilisations like Rome.

Through the poetry of thermodynamics we attain an enriched appreciation of the style of natural science that is appropriate for the constant re-emergence and diffusion of quality. In this, the reflexivity of our relationship with Nature is accepted; the assumptions of simplicity are recognised as abstractions, and the human presence in the scientific process is established, through the recognition of systems uncertainties and decision stakes. In such a science, the traditional norm of puzzle-solving practice for science is superseded; hence we call this new practice 'Post-Normal Science'.

It might seem to be a pessimistic view of things, to deny the Enlightenment project of deploying Science and Democracy in a simple system to bring all of mankind to a guaranteed permanent state of plenty and peace. But that naive vision is now compromised, with so little prospect of rejuvenation that we may really consider it to have (for now) lost all its quality. What alternative source can there be for compassion and commitment? As we have seen, the dialectical tension between quality and its own entropy is never-ending, but it can sometimes be brought to higher levels of awareness. Such an awareness is the best antidote to the despair and apathy of post-modernity as well as to the banalisation and barbarisation of technology-based consumerist culture. The concept of post-normal science, grounded in reflexivity and quality rather than in an unattainable truth or a simplistic good, provides conceptual materials for this endeavour.

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